THE TORNADO: AN ENGINEERING-ORIENTED PERSPECTIVE

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Reprinting Editor's Note

This document is a reprint of NOAA Technical Memorandum ERL NSSL-82. It has been reprinted to serve as a companion document to Southern Region Technical Memorandum NWS SR-146 entitled *A Guide for Conducting Convective Windstorm Surveys* written by William Bunting and Brian Smith. Used together, these two documents will certainly provide a powerful tool for those involved in storm damage assessment and training.

ACKNOWLEDGMENTS

ABSTRACT

Six years of investigations, evaluations and reporting of wind-
storm damage events have provided engineers with their own perspec-
tive of the tornado. This perspective is presented in a manner which
is intended to enhance both the engineer's and meteorologist's under-
standings of the phenomenon. In addition, the presentation of an
engineering-oriented perspective of the tornado serves to establish
and demonstrate the feasibility of designing buildings and facilities
against tornadoes.

Included in the presentation are fundamental concepts of tornado-
building interaction phenomena which are designed to assist the meteo-
rologist in understanding and interpreting wind damage, and to assist
the engineer in assessing wind resistance of building construction.
Illustrations which establish roof to wall anchorages, foundation
anchorages, and windward wall windows and doors as failure initiation
points are valuable to the damage investigator and designer. Major
sections on tornadic windspeeds and atmospheric pressure change advance
the engineering-oriented perspectives that (1) buildings fail at rela-
tively low windspeeds, (2) no conclusive evidence can be found that
ground level windspeeds exceed 250 mph (112 m/s), (3) most building
damage is caused by winds in the 75-125 mph (34-56 m/s) range, and (4)
atmospheric pressure changes in tornadoes play only a minor role in
the damaging mechanism. The performance of housing in tornadoes reveals
that certain types of housing can be relatively good indicators of wind-
speeds in the lower ranges [150 mph (67 m/s) and less], but that
housing damage is an unreliable indicator of windspeed at larger wind-
speed values. Further, orientations of garages, porches, roof over-
hangs, and gables such that the wind attacks these components can pre-
sent unfavorable conditions and invite failure, often leading to er-
roneous observations relating to windspeeds and windfield geometry.

Technical discussions of tornado-generated missiles and unusual
events lead to the conclusion that unusual events associated with tor-
nadoes can be explained by current perceptions of the tornado as defined
by winds and atmospheric pressure change. Missile trajectories estab-
lished from field studies are compared with engineering models to
establish rational assessments of missile events.

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I. INTRODUCTION

Several factors have worked in combination to draw increased public and scientific attention to the tornado: an increased rate of interaction between the tornado and urban environments, the demands of the nuclear industry for tornado-proof structures, and the occurrence of major tornado events such as the Lubbock Storm of May 1970 and the extensive tornado outbreak of April 3-4, 1974. Meteorologists have responded to the new demands for tornado related information with research undertakings on a wide front. Engineers have been less responsive, in general, as designing for such a rare and destructive event as a tornado has, heretofore, seemed impractical.

This report is concerned with the tornado from an engineering point of view. It is suggested early in the presentation that the engineer has something to contribute to the understanding of the tornado phenomenon. Moreover, this contribution has scientific, as well as engineering, implications. The engineering perspective of tornado-induced damage should aid the meteorologist in his assessments of the tornadic windfield while, at the same time, draw the attention of the engineer who is concerned with developing wind resistant designs.

Several major topics of current interest are treated within the report. A basic discussion of building failure mechanisms in windstorms is presented in Section III, as understandings of failure phenomena are important to the treatment of subsequent topics. Following the development of background information on failure modes are treatments of tornadic windspeeds (Section IV) and near-ground windfields (Section V). These perspectives may be of value to both the meteorologist and the engineer. A major section on housing (Section VI) points out the usefulness, and limitations, of housing damage as indicators of windspeed and windfield geometry. Further, this evaluation identifies deficiencies in design which should draw the attention of builders, architects, and engineers. Final topics include the role of atmospheric pressure change in inducing damage, tornado generated missiles, and discussions of unusual events (Sections VII, VIII and IX). A conclusion section summarizes major findings.

II. ENGINEERING EVALUATIONS OF TORNADOES

A. General Objectives

The meteorologist and the engineer share general interests in the tornado as the tornado is becoming an increasingly more important factor in each of their professions. Specific interests vary, however, between the meteorologist and the engineer. The meteorologist is interested in the tornado because he feels responsible for it as an atmospheric scientist and as a weather forecaster. On the other hand, the engineer feels responsible for the tornado because it affects his works--structures and facilities.

It is important to distinguish between the meteorologist's and engineer's interests in the tornado because this difference in perspective affects the manner in which each professional pursues evaluations of the phenomenon. The meteorologist's motivations for study emphasize the scientific understanding of the tornado phenomenon and the need for being able to accurately forecast the conditions which spawn tornadoes. The engineer's motivations are different; his needs emphasize the engineering use of understandings of tornadoes. While each professional is intensely interested in the same phenomenon each has his own needs and, hence, his own manner of approaching the study of tornadoes.

Fortunately, these differences in perspective and approach do not result in bodies of knowledge which are mutually exclusive. The scientific understandings of tornadoes advanced by the meteorologist are used by the engineer. Conversely, the engineer's analyses of the tornado's effects aids the meteorologist in attaining his scientific understanding.

B. Scientific Evaluations of Tornadoes

Advancements in the scientific understanding of tornadoes are occurring rapidly. For the first time, filmed documentations have been made of "secondary" vortices within a parent tornado (Agee, 1975; Fujita, 1974). Much of the satellite, radar, still photography, and eyewitness account data are revealing new and interesting phenomena (Purdom, 1975; Bigler, 1975). Vortex modelers are actively using these data in

their theoretical work and in the laboratory. Hence, the scientific community is active in producing improved characterizations of tornadoes.

This recent activity in the meteorological community is placing demands on the engineering community. Engineers are being called upon to extract data of a scientific nature from heretofore engineering-oriented investigations of damage. General assessments of failure modes and maximum windspeed ranges have been adequate for convincing the practicing engineer that he should upgrade his structural designs, and that he can, in fact, design for tornadoes. However, these assessments are not nearly accurate enough, nor complete enough, for the scientist who is attempting to define, in precise scientific form, the nature of the tornado. Hence, the engineer is challenged to go more deeply into the data and into his catalog of analysis techniques to provide this detailed information. Herein lies, then, a problem for the engineer. He must attempt to conduct certain scientific analyses when he is not equipped with resources (time, money, and training) which will permit him to handle this new undertaking.

Thus, demands beyond those previously encountered in damage analysis are placed upon the investigator charged with making contributions to the scientific understanding of tornadoes. These demands have, first, sent investigators to the scientific literature to assimilate the state of the art for conducting scientific investigations, including the calculation of windspeeds in extreme, turbulent winds. Secondly, these demands have moved engineering investigators to examine damage recording processes to assure that the character of information being obtained can be responsive to the needs of the scientist as well as to his own needs.

C. Engineering Evaluations of Tornado Damage

In view of the observations made above, it can be said that engineering-oriented studies and evaluations of tornado induced damage to buildings and other structures are conducted for two principal reasons. First, understandings of structural response to wind-induced loads are enhanced by such studies. This knowledge leads directly to improvements in the design of wind resistant

structures and, in fact, to procedures which will permit engineers
to design tornado-resistant structures. Secondly, scientific de-
scriptions of near-ground windfields will improve both engineers' and
meteorologists' understandings of the tornado. These understandings
will, in turn, further enhance the engineers' ability to design struc-
tures for extreme wind conditions. Specifically, then, the objectives
of engineering evaluations of tornado damage are twofold:

1   record engineering assessments of the response of structures
    to tornadic loadings--extreme winds, changes in atmospheric
    pressure, and missile impacts; and

(2) advance the scientific understandings of tornadoes through
     the calculation of near-ground windspeeds, the characteri-
     zation of near-ground windfields, and the contribution of
     pertinent facts observed during investigations.

Assessments of tornado-induced damage to structures (Objective
1) fall into a well-established pattern. Documentations contained in
relatively new technical reports by Almuti (1974), McDonald (1970),
Mehta et al. (1971), Sanders et al. (1975), and Walker (1972, 1975)
contain much the same information in the way of damage assessments:

structures fail, principally, because of wind-induced
forces;

non-engineered and "marginally" engineered structures are
susceptible to wind-induced failure at relatively low wind-
speeds because of limited attention to details of design
and construction; and

small increases in degrees of engineering attention (using
new wind engineering technology) can produce very large
dividends in increased wind resistance.

Hence, recent and current work with tornado damage analysis which
address structural failure modes does not contribute a great deal to
previously established knowledge.

It is in the area of scientific understandings of tornadoes (Ob-
jective 2) where the largest advancements can be made. Very large
unknowns characterize the tornadic windfield near the ground. Scien-
tific understandings of this portion of the windfield are dependent
upon the contributions of engineers who are adept at structural fail-
ure analysis methods. The meteorologist must accept what the engineer
is saying about structures affected by this near-ground windfield--

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that all structures are not equal in wind resistance, that structure geometry and orientation are important determinates of wind resistance, and that certain types of structures are very weak where wind resistance is concerned. The engineer, on the other hand, must strive to be more systematic and thorough in his investigations of windstorm damage. He must indicate what information, if any, can be derived from the debris pattern; he must also advance more quantitative information on windspeeds near the ground, with spatial relationships where possible.

The following four subparagraphs advance, as background information, the character of engineering evaluations of tornado-induced damage. The thought that such evaluations can contribute to both the engineering and meteorological communities is traced through these background assessments.

1. Damage Documentation Processes

The manners in which tornado damage is analyzed follows the theme advanced above -- the objectives of the investigation can be engineering oriented (e.g. failure modes of structures), scientifically oriented (e.g. near-ground windfield analyses using debris patterns), or both. In any event, much valuable information on tornado characteristics and tornado-structure interaction can be obtained from systematic, on-the-spot investigations of damage created by a tornado. Physical evidence begins to disappear immediately after the storm. Rescue operations may destroy or modify valuable evidence regarding damage. It is imperative that survey teams reach the damage scene as soon as possible if good field data are to be acquired.

The basic objective of a tornado damage survey is to record storm damage at the scene as quickly as possible, before significant evidence is destroyed. If thoroughly and systematically done, documentations can be studied later to ascertain characteristics of the tornado, structural response to tornadic forces, and weaknesses in design and construction. To achieve this objective, some preparations must be made before the storm occurs, so that survey teams can move immediately to the scene of the storm.

Details of pre-storm preparation activities can be found in material published by the Institute for Disaster Research (1972) and in National Severe Storms Laboratory internal memoranda. In general, the investigation team needs to be selected, briefed, and equipped well in advance. Several three-man teams work best, but two-man teams can work effectively as well. At least one team member must be an experienced structural engineer and, preferably, an experienced wind engineer. Recently, Institute for Disaster Research teams have also included a meteorologist. The addition of this capability has proven invaluable in obtaining the necessary weather data on storm occurrence and in interviewing eyewitnesses.

Briefing activities that should be conducted well in advance include the proper use of credentials, appropriate clothing, communication procedures (between field teams and between the field and the home office), and scopes of activities (aerial work, ground work, securing maps, visiting the weather station, interviews, etc.). Time is a valuable resource when a team is in the field, and care should be taken to assure that all aspects of the storm event are expeditiously covered. Completeness of the investigative effort is best assured through advance planning.

Equipment needed by each team to facilitate documentations include tape recorders (for recording interviews and photograph numbers with descriptions), clip boards with pencils, measurement items (tapes, rulers, calipers), compass, cameras (one with black and white film, one with color film), telephoto and wide-angle lenses, film (enough for 100-200 exposures in each camera), numbering system (for photographs), and flash unit.

Upon arrival at the scene, the team should, first, ascertain the general area of damage. They should identify the tornado or windstorm path, its direction, and the width and length of the damage area. The path should be sketched on a map of the area. The general pattern of damage should be identified by dividing the storm-affected area into destruction "zones". Destruction zone designations refer to the general nature of the damage which occurred within the zone. Three zones are defined (Mehta et al., 1971):

(1) Extensive Damage Zone - A majority of the structures within the zone are destroyed or severely damaged (collapse of loadbearing walls, collapse of structural frames, removal of entire roofs of structures, damage to signs, broken windows, loss of siding, loss of face brick).

Moderate Damage Zone - Approximately one-half of the structures in the zone are significantly damaged (major damage to roofs, toppling of signs, extensive window glass damage, some wall damage).

Scattered Damage Zone - Only a small percentage of structures are significantly damaged (damage to carports, fences, missing shingles and siding).

It may not be possible to identify precisely these zones on the ground immediately. Sufficient photographic documentation should be obtained to permit further classification of these zones later.

Coincident with the determination of the general area of damage, steps should be taken to obtain as much meteorological data about the storm system as possible. Cooperation of the local office of the National Weather Service as well as the weather agencies at the national or regional level can usually be assumed. Efforts should be made to identify and contact other investigation teams who are in the field. Frequent contact with the home office of the field team will facilitate this identification process as the home office can more easily determine the points of contact for other field teams.

The survey team should acquire as many newspaper stories and articles about the storm as possible. Sometimes the information contained therein is not reliable, but many times the stories will provide leads on specific information that may be valuable. Names of persons who provided accounts of events during the tornado should be obtained. These persons should be interviewed directly by the survey team. Damage statistics should also be recorded where possible Sometimes this information can be obtained from governmental agencies (e.g. the local Civil Defense Director). Recording of death and injury locations during the general survey will be helpful. It is also desirable to note damage to public utilities.

Beyond the general type of information noted above as being relevant to any field investigation are more specific information and data which relate to the objectives of the investigation. It is

important for the field survey team to know, in advance, what their principal priorities in investigation will be. Will the investigation be engineering oriented, scientifically oriented, or both? What will be the priorities for documentation; will the field teams emphasize residential construction, engineered construction, debris patterns, or some other aspect of the technology of wind-structure interaction? Summarized below are some of the types of information that can be obtained from engineering-oriented and scientifically oriented investigations.

° Engineering-Oriented Surveys

Experiences with documentations of more than 25 windstorm damage events have indicated that three basic types of photographs are required to document the damage to a specific structure:

Wide-angle, aerial view which shows extent of damage to the surrounding area.

Medium-range view which shows the entire building or complex. Type of construction, type of building materials and general damage should show in these photos. These views may be low altitude aerials or taken from the ground.

Medium and close-range views to show details of construction and/or damage.

Each photograph should have an identification number somewhere within the frame (a number may not be possible in aerial views). A tape recorded photo log is a very effective way to identify the pictures. Included in the photo log is such information as:

(1) Photo identification number,

(2) Identification of the structure and its location (address),

(3) Direction camera is pointing,

(4) Assessment of failure mode, including direction of maximum wind,

(5) Significance of the photo, and

(6) Photo exposure data (f-stop and shutter speed), if under unusual conditions.

Engineering-oriented surveys may include one or more of the following types of investigations:

(1) Failure analyses of fully engineered, pre-engineered, marginally engineered or non-engineered structures.

(2) Analysis of damage to utilities (power plants, transmission lines, treatment facilities).

(3) Documentation of missile events.

(4) Documentation of unusual events.

(5) Recording of detailed data adequate for calculation of damaging windspeeds.

Special care should be taken to record facts pertinent to the translation of large objects such as tanks, automobiles, railroad cars, etc. Identify the size, weight, material and distance traveled. Determine if the missiles were airborne or tumbled to their new locations. Photograph the objects, initial and final location, and travel path, if evident. It is also important to note objects in the damage area that did not translate or structures that did not fail. Such data oftentimes can be used to place upper limits on windspeeds in the area.

° Scientifically-Oriented Surveys

If a more detailed, scientifically oriented investigation is an objective of the field trip, then the focus of the documentation shifts from individual structures and missile events to the general and detailed character of the damage pattern. Institute for Disaster Research investigators have not done many investigations specifically directed toward scientific objectives, but they have conducted certain scientific-level investigations in conjunction with engineering evaluations.

The approach being employed at this time follows procedures outlined originally by Letzmann (1937). A portion of the damage path is selected -- perhaps 500 to 1000 ft (152 to 305 m) along the tornado path in an area of moderate to extensive damage. Local clean-up operations may influence the selection of the study area, as the scientific type of investigation generally takes more time and is more sensitive to disturbance of small debris. A base line in or along the selected area is established and marked (stakes with ribbon) in 50 or 100 ft (15 or 30 m) intervals. Investigators walk along the base line, carefully recording structures, missiles, debris, and unusual observations near the base

line. Major structures and missiles in the damage area are located with respect to the base line. At every 50 or 100 ft (15 or 30 m) stake, investigators move transverse to the base line, making detailed records (notes and photographs) of debris, damage, and unusual observations. Records should reflect such things as the nature, size, orientation, and source of specific debris items; direction of bent or broken items, such as fence posts; scour of ground; nature and direction of tumble marks (caused by missiles such as automobiles); and modes of failure of small structures. These data must be meticulously taken for subsequent plotting on a map and analysis in conjunction with other data.

This procedure, if followed, will focus attentions of the investigators on less obvious damage and will cause them to become inquisitive regarding the sources of debris in given patterns. The importance of this aspect of the investigation must be emphasized. Aerial photographs frequently show "streaks" or "streaklines" of debris (sometimes erroneously related to a streak of wind) which, upon investigation on the ground, oftentimes can be identified with failure of a single, usually weak, building. The systematic recording of debris patter s will not only reveal the cause of the streak, but may establish a windfield direction at that point, along with a probable windspeed.

2. Structural Failures

Windstorm damage investigations conducted by the authors and other engineers (Almuti, 1974; McDonald, 1971; Mehta et al.,1971; Mehta et al.,1975; Mehta et al.,1976; Minor et al.,1972; Sanders et al.,1975; and Walker 1972, 1975) are similar in that they all describe windstorm damage to structures in like terms. Each investigator has come to the conclusion that most buildings are damaged when a connection or an anchorage detail fails, thus leading to collapse of the structure through a progression of component failures. Typically, a poorly anchored roof is lifted by wind-induced forces, thus removing lateral support from the walls which then fall -- usually outward. The most comprehensive treatment of failure modes in various types of structures is contained in the report on the Lubbock Storm of 1970 by Mehta et al (1971) and summarized by Minor et al. (1972). After six years of additional investigations by these authors and others, the

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fundamental assessments made therein continue to be perceptive.

Hence, the understanding of building failures in windstorms, including tornadoes, is relatively well advanced. This knowledge and boundary-layer wind tunnel technology have combined to produce significant advances in the portions of building codes which address wind loads. The new American National Standard Building Code Requirements for Minimum Design Loads in Buildings and other Structures (ANSI, 1972) is an example of this advancement in the United States. The Canadians (National Research Council of Canada, 1975), the British (BSI, 1972), and the Australians (Standards Association of Australia, 1975) are even more advanced in terms of incorporation of this knowledge into the practice of engineering.

The point being made in this background discussion is that engineering evaluations of tornado induced damage have produced relatively well-advanced understandings of building failure modes. This understanding forms the basis for discussions advanced in Section III on structural failure mechanisms and in Section VI on the performance of housing, and forms a part of the discussion of atmospheric pressure change in building failure in Section VII.

3. Missile Events

Concerted efforts have been made in conjunction with building failure investigations to record missile incidents in tornadoes. While considerable amounts of data have been recorded, the understandings of object injection, flight, and impact are not as advanced as are the understandings of building failure modes. In this field of tornado phenomenology there has been a considerable amount of theoretical work. Models of tornadic windfields are utilized with various assumed flight characteristics of specific missiles in computer-oriented formulations which predict flight paths, velocities, and impact orientations. Relatively new to these formulations are probabilistic methods which are used to consider such things as the probability of tornado occurrence, probability of missile presence, probability of injection, probability of "end-on" orientation at strike, etc. Used principally in the nuclear industry, these theoretical treatments are valuable tools for research and design. As yet, however, there have not been sufficient verifications of any one method (through comparison with field documen-

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tations) for a consensus formulation to have emerged.

With additional reference to engineering vs. scientific documentations (Ref. Section II.B), it must be pointed out that documentations of missile events have been more engineering, than scientifically, oriented. Records of single, more or less isolated, incidents have been made. Generally, records contain data of an engineering type -- missile weight and geometry, original and final locations, and impact damage. Needed in this area is more attention to records of a scientific nature -- systematic recording of debris and damage patterns in the immediate area surrounding the missiles of interest. Data are needed which can relate the missile event to the near-ground windfield in order to aid in the formulation and verification of theoretical characterizations noted above.

In any case, missile event analysis forms an integral part of the damage documentation process. The presentation contained in Section VIII is a state of the art discussion of missiles in tornadoes, including overviews of field data and theoretical formulations.

4. Other Analyses

Engineers who have conducted damage documentations to date are aware of the needs for answering scientifically-oriented questions regarding the tornado's structure -- windfield geometry, windspeed maxima, and atmospheric pressure change. While aware and eager to contribute, they are not equipped by training or with resources to conduct the required depths of scientific investigation. Nonetheless, certain of the engineering evaluations available in the literature contain data which can contribute to the scientific understanding of tornadoes. These data relate, principally, to tornadic windspeeds, the geometry of near-ground windfields, and the magnitude of atmospheric pressure change in tornadoes.

An assessment of the probable maximum windspeed in a severe tornado was reported by engineers following the Lubbock Storm of May 1970 (Mehta et al., 1971). In this very large, quite destructive, and extensively studied tornado, engineers reported no evidence of ground level windspeeds exceeding 200 mph (89 m/s). Subsequent studies of other tornadoes (Almuti, 1974; Mehta et al., 1976) also suggested that near-ground windspeeds exceeding the 200-250 mph (89-112 m/s) range cannot be

substantiated. There are, however, some uncertainties associated with these assessments as the definition of coefficients of drag in turbulent, accelerating wind regimes is not well established. Discussions of maximum tornadic windspeeds assessed by engineers are presented in Section IV.

Near-ground tornadic windfields are, of course, also of concern to the engineer. Again, his engineering evaluations are useful to the understanding of this part of the tornado's structure, but, generally, the documentations accomplished for recent tornadoes do not provide a comprehensive perspective. A summary of what is known, and what is needed, is advanced in Section V.

The role of atmospheric pressure change in causing building damage has been of interest to the engineer (and the layman) for some time. Analyses of damage documentations suggest that (1) the magnitude of pressure change in the center of the tornadic windfield at ground level is not nearly so large as once thought and (2) the change in atmospheric pressure plays a minor role in the damage process relative to the role played by winds. Again, the engineering data which support these observations are conclusive relative to building damage, but scientific analysis of the character of the pressure field near the ground has not been accomplished. Discussions of atmospheric pressure change near the ground are advanced in Section VIII.

Finally, engineers have been careful to take note of several unusual phenomena which have been reported to occur in tornadoes. Commonly reported are ponds and pools of water being "sucked" dry, straws being driven through wooden planks, and phenomenal missiles. It is felt that these reports are often overstated, for when physical facts were recorded it has been ascertained that the phenomena either did not occur as reported or are easily explained through scientific analysis. Discussions of some of these phenomena are presented in Section VIII.

III. STRUCTURAL FAILURES FROM TORNADIC EFFECTS

A   Modes of Failure

Extensive documentation, analysis, and evaluation of windstorm-caused building failures have produced a relatively well-established consensus which describes tornado-structure interaction phenomena. The discussion and references cited in Section II tend to support a general contention that wind action plays a dominant role in the failure of conventional structures, although the presence and effects of atmospheric pressure change are acknowledged. Windborne missiles may also play a role in inducing certain types of structural failure.

The objectives of this section of the report are twofold. First it is important that a fundamental understanding of the mechanisms of structural failure as induced by tornadic effects be established. This understanding can be used by scientists and engineers who are called upon to make objective analyses of tornado damage. Secondly, certain fundamental understandings of tornadic effects on structures are essential to the treatment of topics found elsewhere in this report. Discussions of tornadic windspeeds, near-ground windfields, atmospheric pressure change, missiles and unusual phenomena will be based upon these basic understandings of structural failure. Although interrelated as they affect structures, the three tornado induced effects which influence structures -- wind, atmospheric pressure change and windborne missiles -- are discussed separately in the following paragraphs.

1   Wind Effects on Structures

A major area of interest concerns how air flows around buildings and, in so doing, produces forces for the structural engineer to address, and produces aerodynamic situations for treatment by the mechanical engineer. Phenomena associated with air flow around buildings are the product of "wind-structure interaction." This topic has received extensive attention from structural engineers in recent years, and has become increasingly more interesting to mechanical engineers as they design heating, ventilation, and air conditioning systems.

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° <u>Wind-Structure Interaction Concepts</u>

When a turbulent wind approaches and envelops a structure, the direction of air flow is changed. This change in flow direction is reflected in several phenomena which are apparent near and on the surfaces of the structure. If a structure is visualized as consisting of five surfaces (four walls and a roof) with wall corners, eaves (wall/ roof corners), roof corners, and roof ridges (Fig. 1), then certain phenomena which influence each of these parts of the structure can be identified. The phenomena of interest may be divided broadly into two types: overall phenomena and local phenomena.

In an overall sense, the general pattern of air flow will produce an inward-acting pressure on a windward wall (called "stagnation" pressure because on this surface the air tends to stop or "stagnate" in front of the windward wall) and outward-acting pressures on the two side walls, the leeward wall and the roof (Fig. 2). Outward pressures occur on four of the five surfaces because the air flow is accelerated to a higher velocity as it travels the longer distance around or over the structure, and because the air flow "separates" from the surface of the building at windward wall corners, eaves, and ridges, thus creating low pressure pockets or "bubbles" downstream from separation points.

In a local sense, the flow of air cannot negotiate the sharp corners at wall corners, eaves, roof ridges, and roof corners; hence, the flow separates from these structural surfaces (Fig. 3). Relatively low pressures which occur immediately downstream of these flow separations are principal causes of many structural failures and the malfunction of certain types of mechanical systems. Concentrations of relatively low pressure occur along surfaces immediately downwind from flow separation points as shown in Figure 3. In addition, because of the turbulence present in the approaching wind, the flow separation line tends to fluctuate, causing wake turbulence downstream from separation points. This wake turbulence may affect, dynamically, wall components (e.g. windows) or roof components (e.g. roof panels), as well as mechanical equipment located in these areas. If the wall or roof downstream from the separation point is very long, the air flow
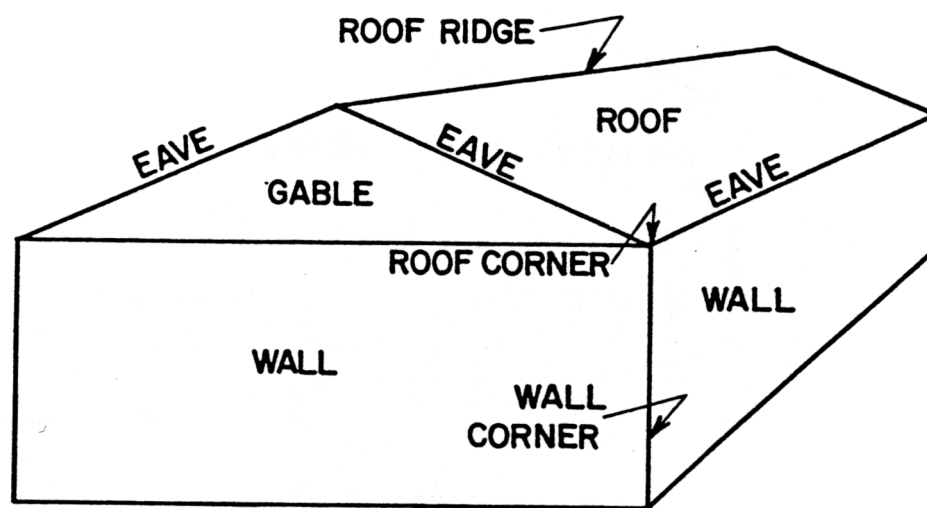
FIGURE   TERMINOLOGY EMPLOYED IN DESCRIBING WIND-STRUCTURE
INTERACTION PHENOMENA. Building components are
termed windward, leeward, or side depending upon
wind direction.
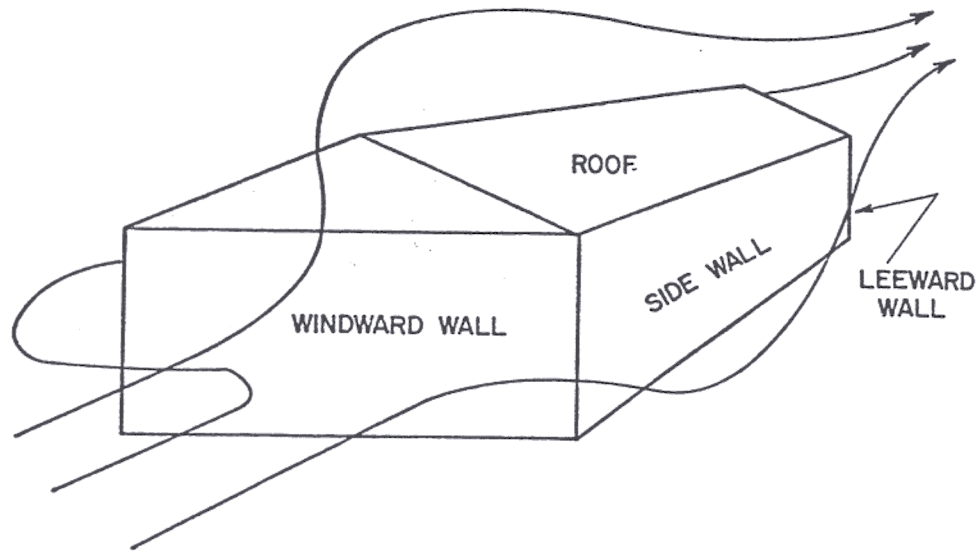
AIR FLOW AROUND STRUCTURE
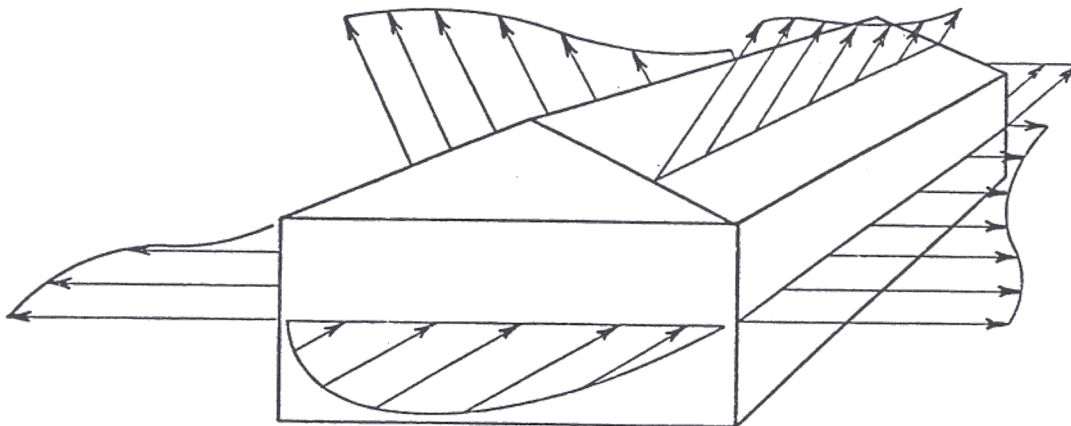
OVERALL PRESSURES ACT OUTWARD ON ROOF, SIDEWALLS,
AND LEEWARD WALL

FIGURE 2. AIR FLOWS AROUND STRUCTURES INDUCE PRESSURE
ON BUILDING COMPONENTS. Note that five of
six surfaces experience outward-acting
pressures.

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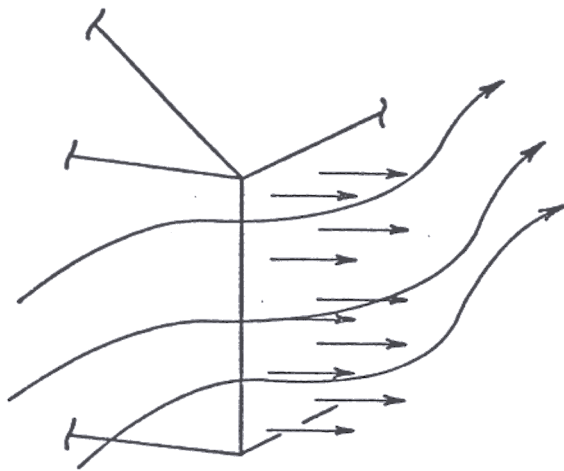
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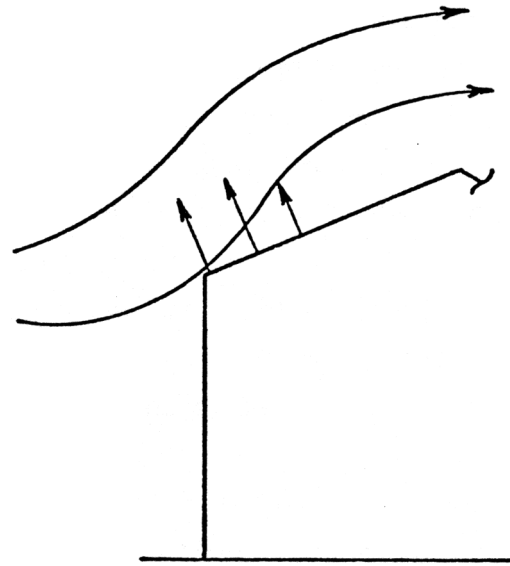
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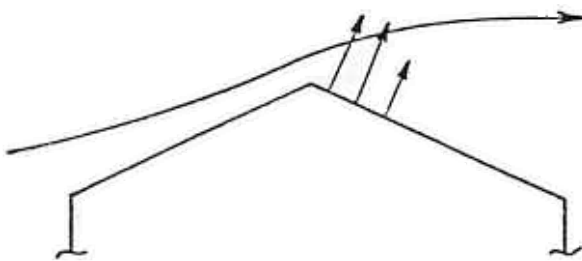
ROOF RIDGES
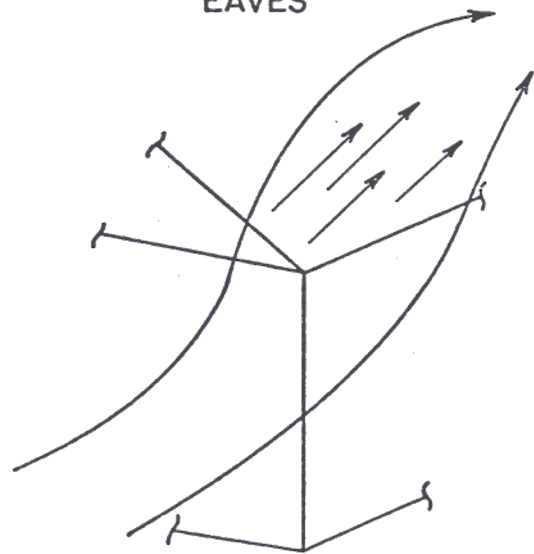
ROOF CORNERS

FIGURE 3.   AIR FLOWS ACROSS SHARP CORNERS INDUCE PRESSURE
             CONCENTRATIONS.   These points often become
             failure initiation points.

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may reattach to the structure; otherwise, the wake turbulence can affect an entire wall or roof.

Two important observations can be made at this point relative to wind effects on structures. First, it is clear that wind, acting alone, produces outward-acting pressures on all surfaces except the windward surface. Secondly, the aerodynamically poor character of most conventional buildings invites relatively large outward-acting pressures along sharp edges (roof ridge, roof corner, eave, wall corner) These observations have relevance to ensuing discussions relative to building "explosions" under the influence of the tornado's effects.

Before proceeding to a discussion of modes of structural failure, a final, but very important, facet of wind-structure inter-action phenomenology must be advanced. This facet of the science concerns pressures which occur when openings appear in the structure, either by design or through component failure. Figure 4 illustrates the effects of such occurrences. An opening in a windward wall causes an increase in pressure within the building. This pressure increase combines with the outward-acting pressures already acting on the roof, the leeward wall and the side walls to compound the outward-acting forces on these surfaces. This increase in internal pressure tends to relieve the net pressure acting across the windward wall. Conversely, an opening in the side walls or the leeward wall causes a decrease in pressure within the building. This pressure decrease combines with the inward-acting pressure on the windward wall to compound the inward-acting force on this surface. The internal pressure decrease tends to relieve outward-acting net pressures across the roof, side walls, and leeward walls.

The above observations have direct relevance to the often quoted concept of opening a window in the face of an impending wind-storm in order to "relieve pressures." Setting aside the role of at-mospheric pressure change for a moment (discussed in subsequent sections), it is clear that:

( ) an open window on the windward surface will help protect the windward wall, but accentuates pressures acting across the roof, side walls, and leeward wall, and

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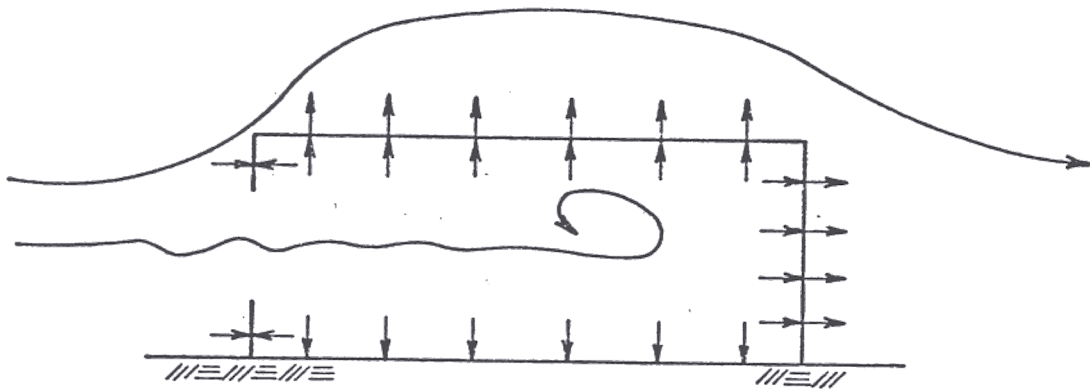
OPENING IN WINDWARD WALL CAUSES PRESSURE INCREASE
INSIDE, AND COMPOUNDS PRESSURE EFFECTS ON ROOF,
LEEWARD WALL, AND SIDEWALLS.
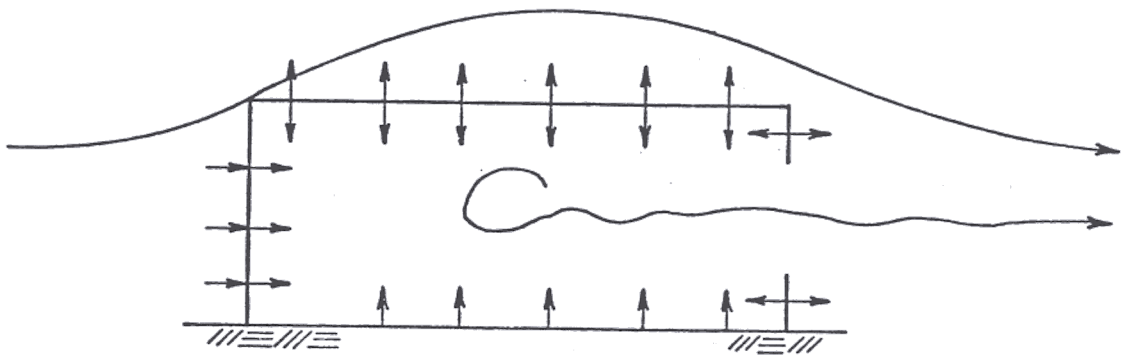
OPENING IN LEEWARD WALL CAUSES PRESSURE DECREASE
INSIDE, COMPOUNDS PRESSURE EFFECTS ON WINDWARD WALL
AND RELIEVES PRESSURE ON ROOF.

FIGURE 4. OPENINGS IN BUILDINGS RESULT IN INTERNAL PRESSURE CHANGES WHICH CAN BE
DETRIMENTAL TO STRUCTURAL INTEGRITY. Opening a leeward window may
help hold the roof on, but compounds pressure across windward wall.

(2) an open window on the side or leeward surface will
help hold the roof on and will tend to decrease net
pressures acting across side and leeward walls, but
will compound the pressures acting across the wind-
ward wall.

Hence, the idea that a window should be left open when a windstorm
is imminent has some implications, the results of which may not be
immediately clear to the person opening the window. In the event
of a tornado occurrence the specific window left open could as
easily become a windward wall window as a leeward wall window, since
the direction of attack of the wind is uncertain. While opening a
leeward wall window has certain advantages, the opening of a wind-
ward wall window is clearly detrimental to the structure. In the
event of a hurricane (or a cyclone or a typhoon) where, presumably,
the direction of wind attack can be established in advance, the open
leeward wall window will help hold the roof on, but it will result
in an increase in the pressure acting across the windward wall. The
advisability of taking such action will depend, of course, upon the
characteristics of the structure at issue. Generally, one story
structures, particularly housing, tend to be weaker in their roof to
wall connection than in their wall strength; hence, the opening of a
leeward wall window may be advisable, but only when the direction of
the attacking wind can be established.

° Examples of Wind Effects Reflected in Failure Modes
The wind-structure interaction concepts advanced above
can be best illustrated by viewing some examples of wind-damaged struc-
tures. While atmospheric pressure change may have been present in some
of the examples cited and could have played a role in the failures,
analysis has shown that wind action was clearly the dominant factor.
Figure 5 illustrates the general effects of air flow around buildings.
A windfield has acted to lift the roof of this house, allowing the side
and leeward walls to fall outward. The windward wall has been pushed
inward or in by wind-induced forces. This mode of failure is not un-
common in residential structures exposed to tornadic winds. Oftentimes
the appearance of the failed structure gives rise to the concept that the

22

WINDWARD WALL (INWARD)

ROOF

SIDE WALL (OUTWARD)

LEEWARD WALL (OUTWARD)

H 02
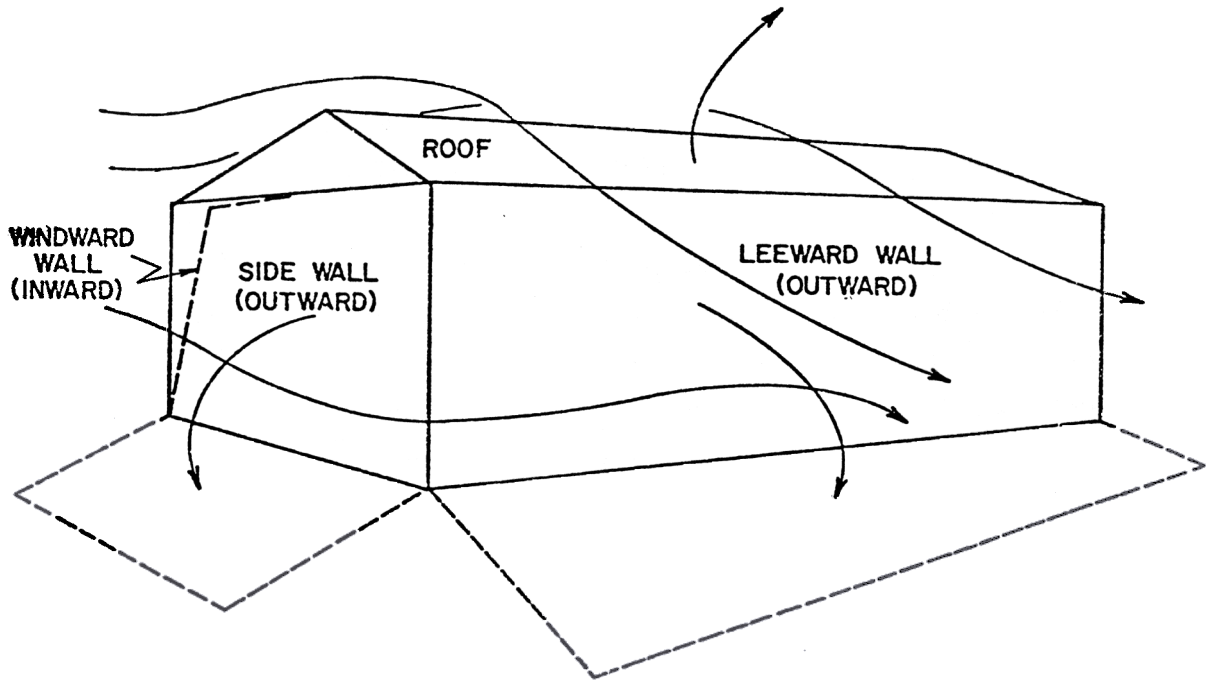
FIGURE 5. WINDS ACTING ON RESIDENTIAL STRUCTURE CAUSED CLASSIC FAILURE MODE
Three walls and roof experienced outward-acting pressures.

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structure "exploded" because of an atmospheric pressure change. More often, engineering analysis reveals that the roof was lifted first and the walls, being no longer supported at the top and being restrained from falling inward, toppled outward. Although this particular view is of a tornado-damaged house in Hereford, Texas, many hurricane (straight wind) damaged houses exhibit the same failure mode.

The windward wall of the gymnasium that is illustrated in Figure 6 has fallen inward. This failure in Joplin, Missouri was the result of inward-acting (stagnation) pressure on a large vertical surface which was presented to the wind. The structural engineer must exercise care designing this type of wall as very large total forces are encountered. In this specific case a weak roof to wall connection may have been a factor in the failure. If the roof lifted first (because of local, upward-acting pressures along the windward eave), the wall would have been free-standing, in effect, between the two vertical construction joints.

The effects of a general wind-structure interaction condition can also be seen in Figure 7. The windward wall of this building fell inward, the side walls fell outward, and the roof lifted upward. Here, there is evidence that early failure of the windward wall (possibly failure of an overhead door) allowed pressure to build inside the structure. Thus, outward acting forces on the walls and roof caused by air flowing around the building were assisted in causing damage by an increase in pressure inside the building. This failure mode -- observed in Atlanta, Georgia -- is common when large glass windows or overhead doors in the windward wall fail (or are left open). The same phenomenon can occur when a mechanical equipment grille permits stagnation pressure on the face of a windward wall to be transferred inside the building.

The engineered church structure illustrated in Figure 8 survived the direct effects of a severe tornado which traveled through Omaha, Nebraska in May 1975. Air flowing over and around the structure separated from the surfaces at roof corners, eaves, and roof ridges, causing locally severe upward-acting pressures. Damage to the roof

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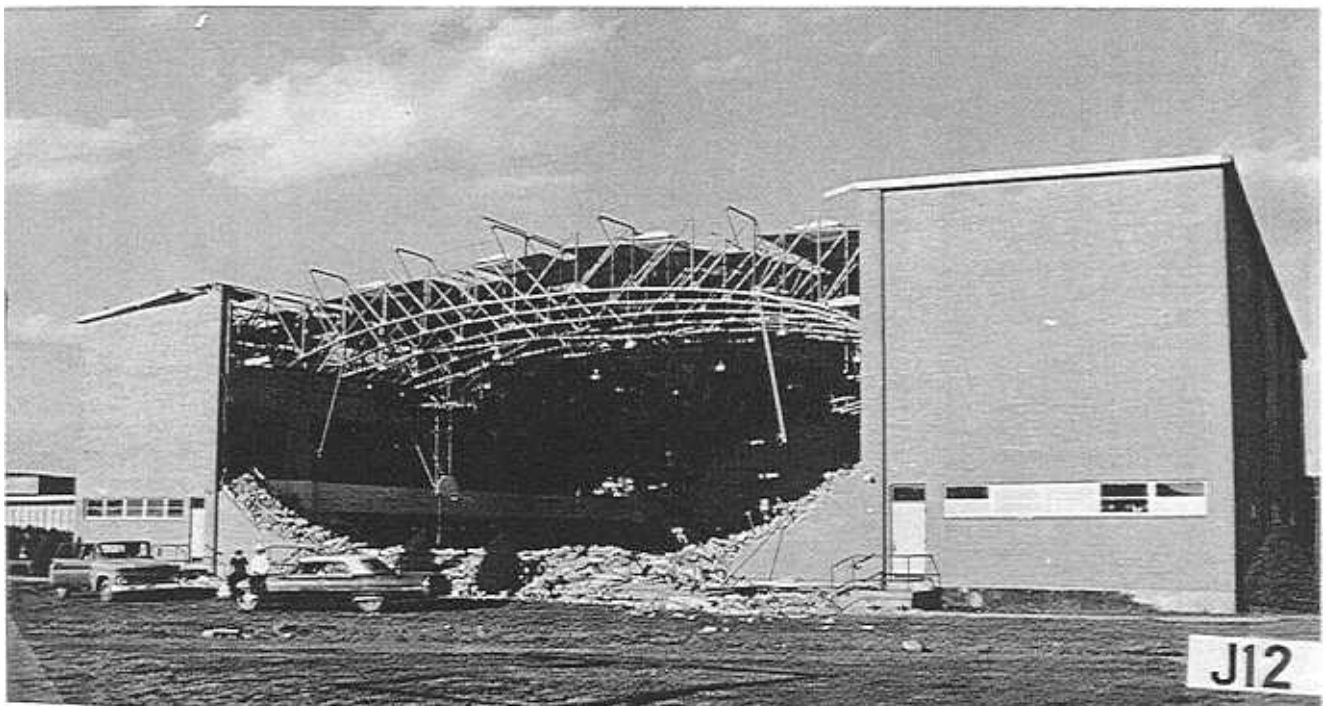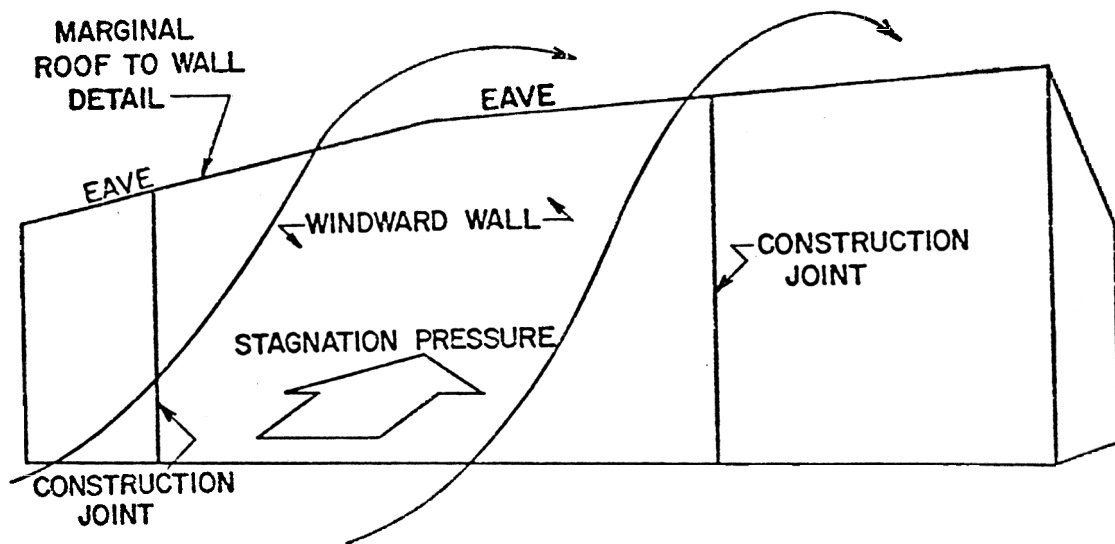
FIGURE 6. WIND-INDUCED PRESSURE ON WINDWARD WALL CAUSED FAILURE OF MASONRY.
Concrete block and brick wall fell inward.
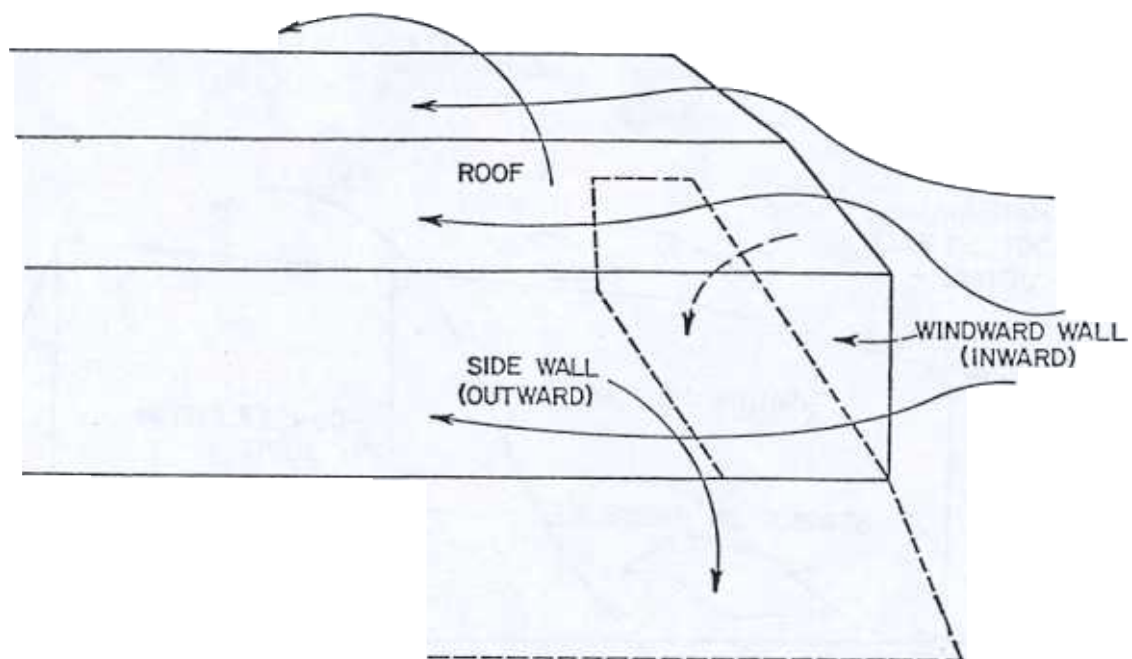
FIGURE 7.   EFFECTS OF WIND ENTERING BUILDING AFTER FAILURE OF WINDWARD WALL.
Side walls and roof failed outward, assisted by internal pressure.
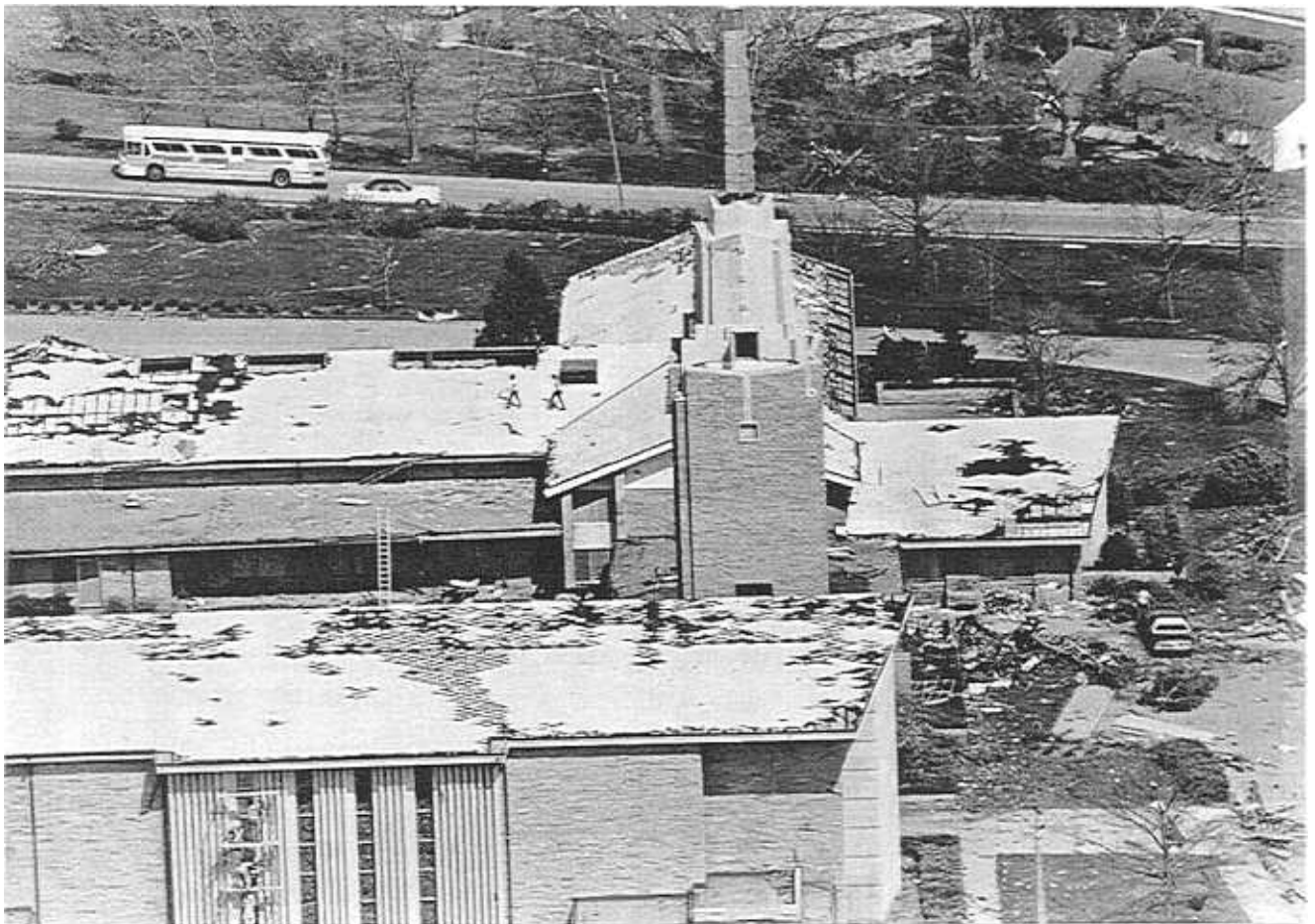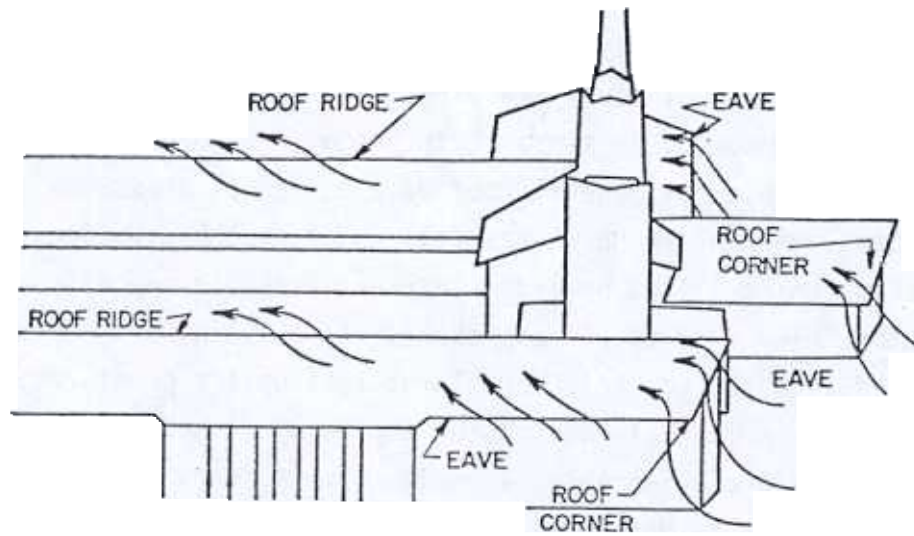
FIGURE 8. AIR FLOW OVER FULLY ENGINEERED CHURCH BUILDING CAUSED LOCAL FAILURE
AT EAVES, RIDGES, CORNERS OF ROOF. Local pressures can be very
large and often induce progressive failure.

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reflects these local effects. Note in this photograph that eaves with overhangs are particularly vulnerable to local wind effects.

Corners of roofs are especially vulnerable to local wind effects. The school in Xenia, Ohio shown in Figure 9 received corner roof damage, but not general roof damage. Local pressures acting under the overhanging beams, as well as along the eave line, caused the beams to be lifted upward. Internal pressure may also have been a factor. The flow of air approached the building from an angle directed into the corner. Very large roof uplift pressures can be experienced for certain horizontal angles of attack of the wind. Wall corners are vulnerable, as well. The masonry walls at the corner of the Atlanta warehouse shown in Figure 10 experienced locally severe,outward-acting pressures during a windstorm in March 1975.

2. Atmospheric Pressure Change

Atmospheric pressure change that is present within the tornado vortex acts to create outward-acting pressures across all surfaces of a building. A building which is "sealed" so that no air can escape as the tornado passes will experience pressure differences across each wall and roof component equal in magnitude to the change in atmospheric pressure induced outside by the tornado. Furthermore, the rate at which the pressure changes occur is dependent upon the translational speed of the tornado as it crosses the building. Thus, in an ideal, theoretical sense, pressure effects caused by atmospheric pressure change are real and may be depicted as illustrated in Figure 11.

Actual pressures experienced by conventional building components as the result of atmospheric pressure change are quite different from those postulated by the above ideal case. Any variation from a sealed condition will significantly reduce the magnitude of the pressures which act across wall and roof components, since air will escape through openings as the tornado approaches. Furthermore, as the translational speed of the tornado becomes slower, the effects of atmospheric pressure change on an unsealed building become less severe. The effects are mitigated because air inside the building

LOCAL UPLIFT DUE TO
FLOW SEPARATION

ROOF BEAMS
(UPWARD)

STAGNATION PRESSURE
UNDER OVERHANG

WINDWARD WALL
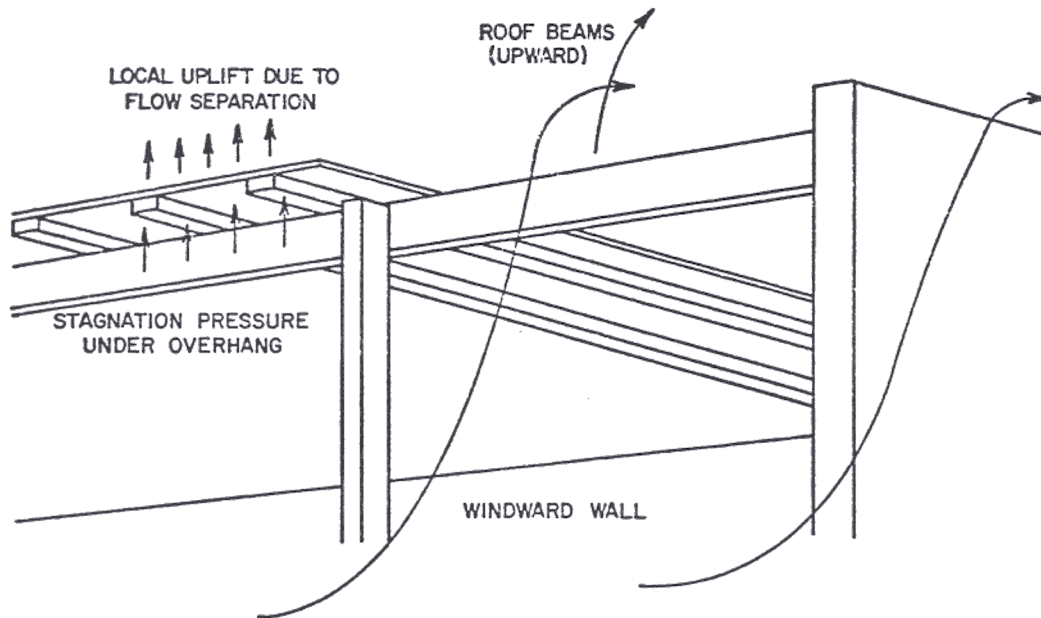
FIGURE 9. UPWARD-ACTING PRESSURES LIFTED "DOUBLE T" BEAMS FROM SCHOOL.
Failure of windows, overhang, and air flow over roof con-
tributed to failure.

29
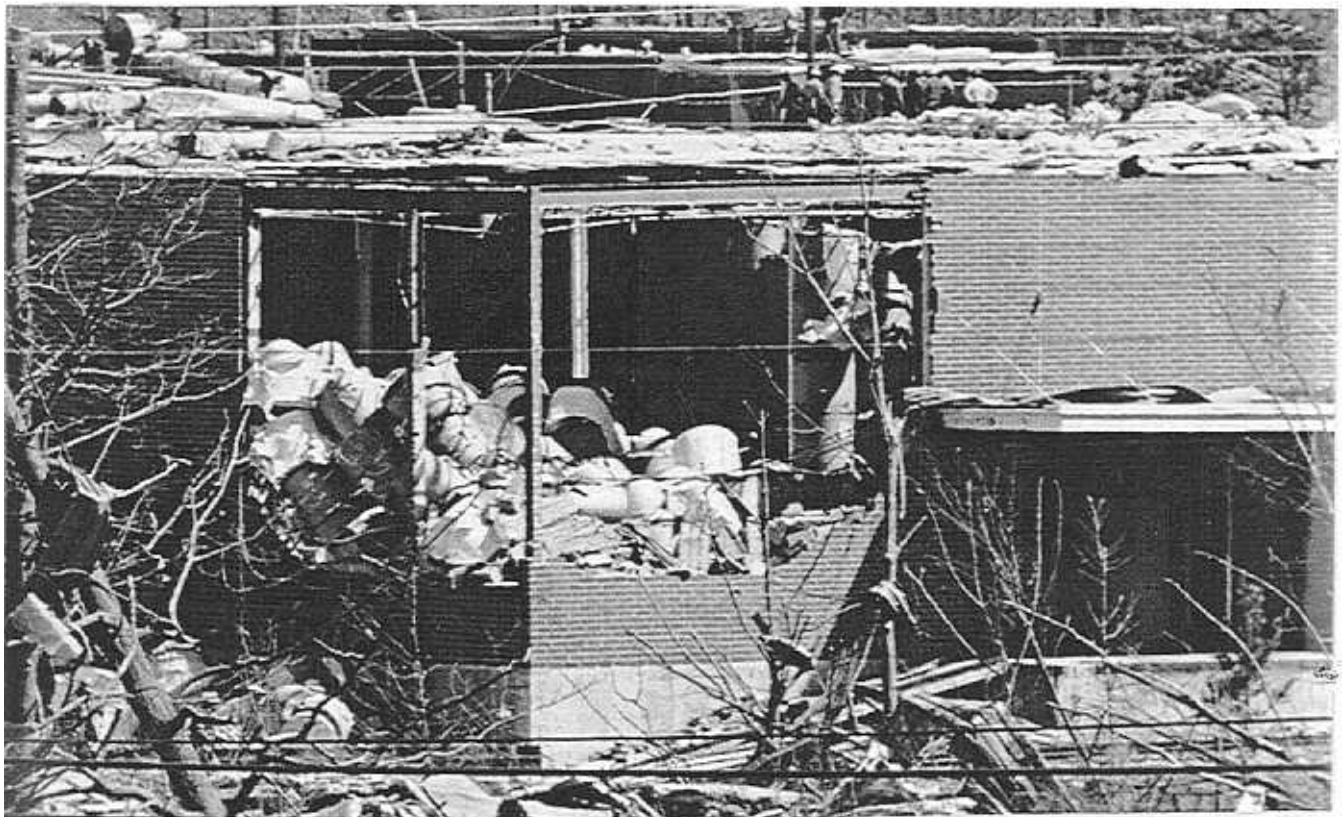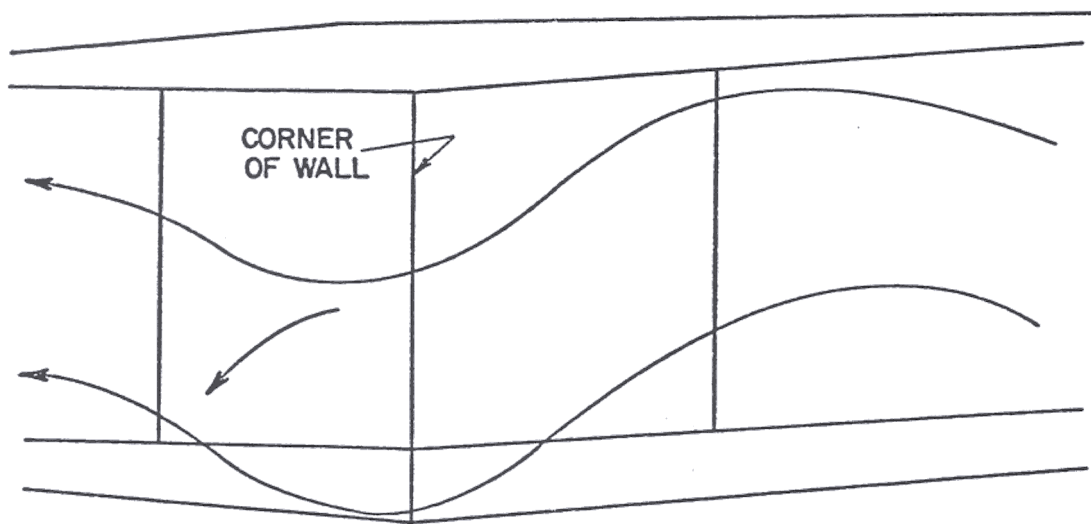
CORNER
OF WALL

FIGURE 10. AIR FLOW AROUND CORNER OF BUILDING CAUSED WALL FAILURE.
Locally severe, outward-acting pressures occur at
corners of walls.

TORNADO APPROACHES · TORNADO OVER STRUCTURE · TORNADO PASSES
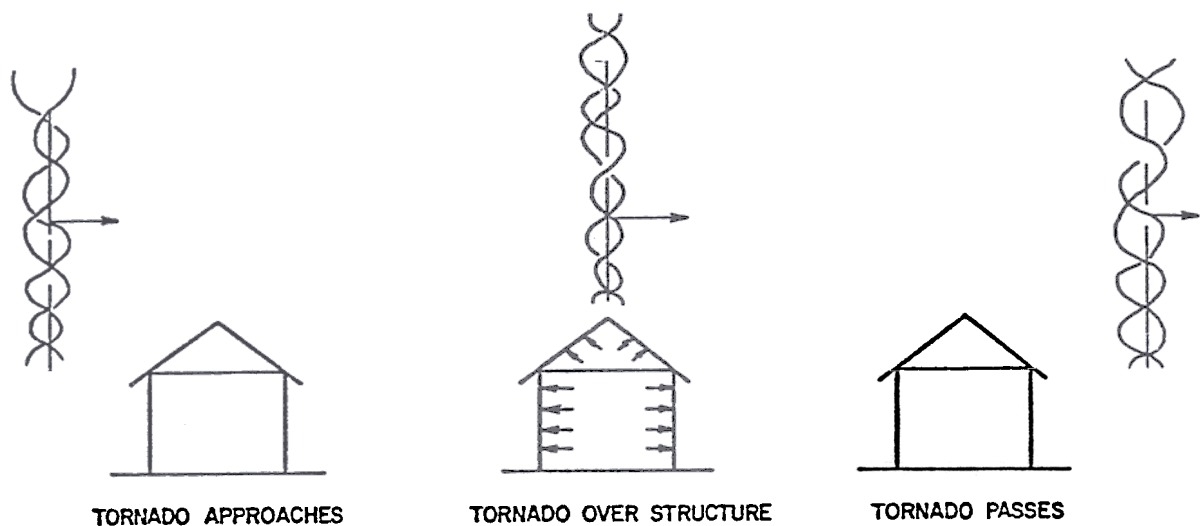
SEALED BUILDING EXPERIENCES EFFECTS OF ATOMSPHERIC
PRESSURE CHANGE

TORNADO APPROACHES · TORNADO OVER STRUCTURE · TORNADO PASSES
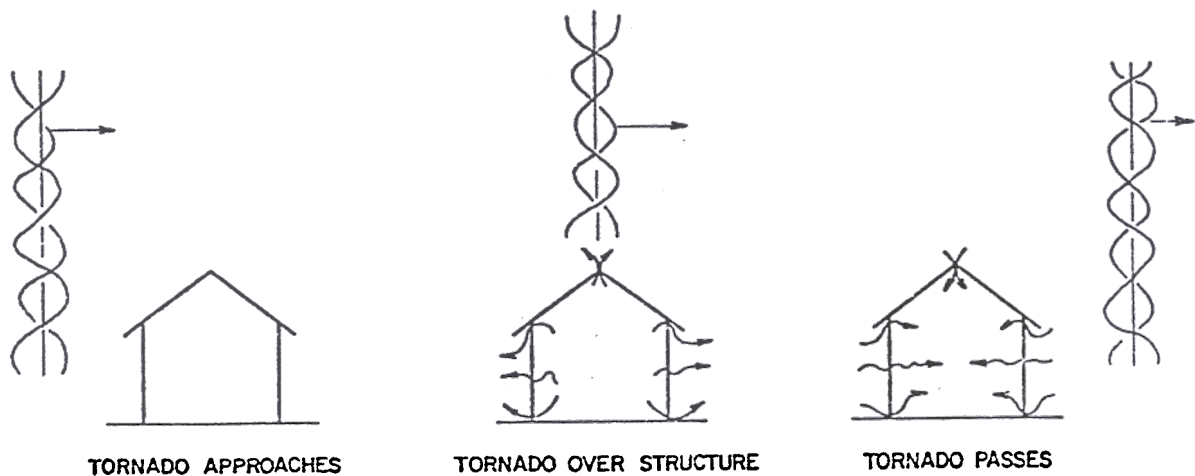
UNSEALED CONVENTIONAL BUILDINGS ALLOW AIR TO ESCAPE, THUS
TENDING TO RELIEVE EFFECTS OF ATMOSPHERIC PRESSURE CHANGE

FIGURE 1. EFFECTS OF ATMOSPHERIC PRESSURE CHANGE.
Normal venting in conventional buildings
is often adequate to mitigate this effect

has more time to escape and, thus, maintain relative equilibrium between inside and outside pressures.

Several observations can be advanced to support previously stated contentions that the effects of atmospheric pressure change play minor roles, relative to wind effects, in the failure of conventional structures. First, the magnitudes of windspeed and pressure change in tornadoes are considerably lower than the extreme values often quoted or implied (See discussions of tornadic windspeed, Section IV, and atmospheric pressure change, Section VII). Secondly, barograph recordings from the rare events in which a tornado crosses a weather station indicate that these deficits are relatively small, the largest ever recorded being only 34 mb (0.5 psi) (Davies-Jones and Kessler, 1974). Thirdly, relatively small openings in buildings can be expected to effectively vent the structure for average tornado translational velocities. For example, openings on the order of one square foot (0.9 m^2) for each 1000 cubic feet (28.3 m^3) of building volume will limit air velocities through the opening to 25 mph (11.2 m/s) or less for the 260 mph (116 m/s) tornado noted above, if the translational velocity of the tornado is such that the pressure change (from ambient to minimum or from minimum to ambient) occurs in 3 seconds or more (See calculations presented in Section VII). Finally, severe winds affect structures before atmospheric pressure change can become a factor; hence, component failures caused by wind action oftentimes open the structure and eliminate any tendency toward air tightness before the atmospheric pressure change has an opportunity to become a factor.

Essentially all structural failures observed by engineers in the wake of tornadoes can be more rationally explained through the consideration of wind effects than through consideration of the effects of atmospheric pressure change. Hence, no examples of failures where atmospheric pressure change was a principal effect can be advanced here.

Furthermore, searches in the debris for evidence of radical changes in pressure (e.g. exploded beverage containers, bulging mason jar lids, opened paint cans, etc.) have produced no conclusive evidence that radical changes in atmospheric pressure occur at ground level.

3. Windborne Missiles

Wind is clearly the most prevalent tornadic effect which causes failures of structures. Direct effects of the wind act on buildings in the manner outlined in Section III.A-1. Wind is an indirect cause of other failures through the action of windborne debris which impact on structures. Two effects of windborne debris serve to compromise the integrity of the structure and, therefore, are the causes of failure: (1) impact on non-structural components and (2) impact on principal structural frames.

Windborne debris can impact upon non-structural components such as windows, doors, and "fill-in" walls"* in a manner which causes component failure and allows wind to enter the structure. Once the integrity of the building has been compromised, the principal structural frame can be damaged through one of the mechanisms outlined in Section II.A. Figure 12 contains illustrative examples of windward wall failures which were caused by windborne debris.

In some instances, large items have tumbled or blown into components of the principal structural frame. Such windborne missile incidents have a potential for inducing, directly, failure of the structural system through excessive structural response. Records of such impacts are rare, and the impact does not always, in itself, cause the failure. Figure 13 illustrates how a major missile can cause failure of the principal structural system.

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*As used in this report, a "fill-in wall" is a non-structural wall component which fills the space within components of a structural framing system which may be steel, reinforced concrete or wood.

FIGURE 12. MISSILES CAN PENETRATE WINDWARD WALLS.
Damage induced by missiles can lead
to failure of wall components.

FIGURE 13. MISSILES MAY IMPACT PRINCIPAL STRUCTURAL FRAMES OF
BUILDINGS CAUSING COLLAPSE. Oil tank in center left
of photograph traveled 600 ft (183 m) to impact metal
building.

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B. Performance of Buildings in Windstorms

Several years of attention to wind caused failures in buildings has produced a relatively well-advanced understanding of the manner in which winds affect buildings of all types. Further, this attention to the study of damage has produced a classification of buildings according to the character of response which they exhibit. Advanced originally in the comprehensive report on the Lubbock Storm (Mehta et al., 1971) and in an article in the Structural Journal of ASCE (Minor et al., 1972), this classification scheme recognizes differences in relative resistance of buildings in relation to the amount of engineering attention given to them. Other authors have advanced the same or similar schemes in reporting damage (Walker, 1972; Walker, 1975; Sanders et al., 1975). In this method, buildings are classified as fully engineered buildings, pre-engineered buildings, marginally engineered buildings, and non-engineered buildings. Discussions of the response exhibited by these structures will assist the reviewer of windstorm damage in assessing building failures and in placing the oftentimes awesome appearing damage into a proper perspective with respect to attendant damage-causing windspeeds.

1. Fully Engineered Buildings

Buildings which receive specific, individualized design attention from a professional architectural-engineering firm are called "fully-engineered". Several fully engineered buildings have been impacted directly or nearly directly by tornadoes. If the building has received the degree of detailed engineering attention that is representative of the standard of practice for major buildings, its performance in the face of extreme winds is likely to be very good. A hospital in Omaha, Nebraska which was impacted directly by the Omaha Tornado of May 6, 1975, typifies this performance. This building was comprised of a reinforced concrete frame with reinforced concrete floor slabs of pan type construction ("waffle" appearance when viewed from underneath). The reinforced concrete roof of the structure was also of pan type construction. Damage to the part of the hospital which was built in this manner was limited to broken windows, a limited number of "fill-in wall" failures, and some interior

partition failures (Fig. 14). The Great Plains Life building in Lubbock experienced winds peripheral to the Lubbock Tornado of May 11, 1970 which were sufficient to severely wrack the structure leaving a permanent deformation in the structural steel frame. While the frame was permanently deformed, the exterior masonry was cracked, and interior partitions were broken, the building was not at any time near collapse. The building has been repaired and restored to useful service (Fig. 15). The First National Bank - Pioneer Natural Gas Company Building in Lubbock experienced similar winds during the same storm (Fig. 16). Windows were broken on both windward and leeward faces of the building, and considerable damage was done to interior furnishings. The reinforced concrete building frame was not damaged and the building was restored to service.

The principal observation to be made in reviewing tornado-induced damage to fully engineered structures concerns the appearance of the damage. Oftentimes such a structure appears in a tornado damage path as a building which escaped damage, when buildings on either side were destroyed. Often it is assumed, or concluded, that the tornado "skipped over" the engineered building when, in fact, it was simply better able to withstand the forces applied by the tornado. Similarly, windspeed estimates are sometimes made by looking at the extensive damage done to a non-engineered building, like a house, when a more accurate estimate could be developed by examining the more predictable behavior of a fully engineered structure.

2. Pre-Engineered Buildings

A unique classification of buildings described as "pre-engineered" metal buildings has been exposed to extreme wind effects (tornadoes and hurricanes). These buildings receive engineered attention in advance; the buildings are subsequently marketed in many units throughout the country. Many manufacturers of these units do an excellent job of "balancing" the engineered design so that all components are equally strong; hence, an optimum economy of construction
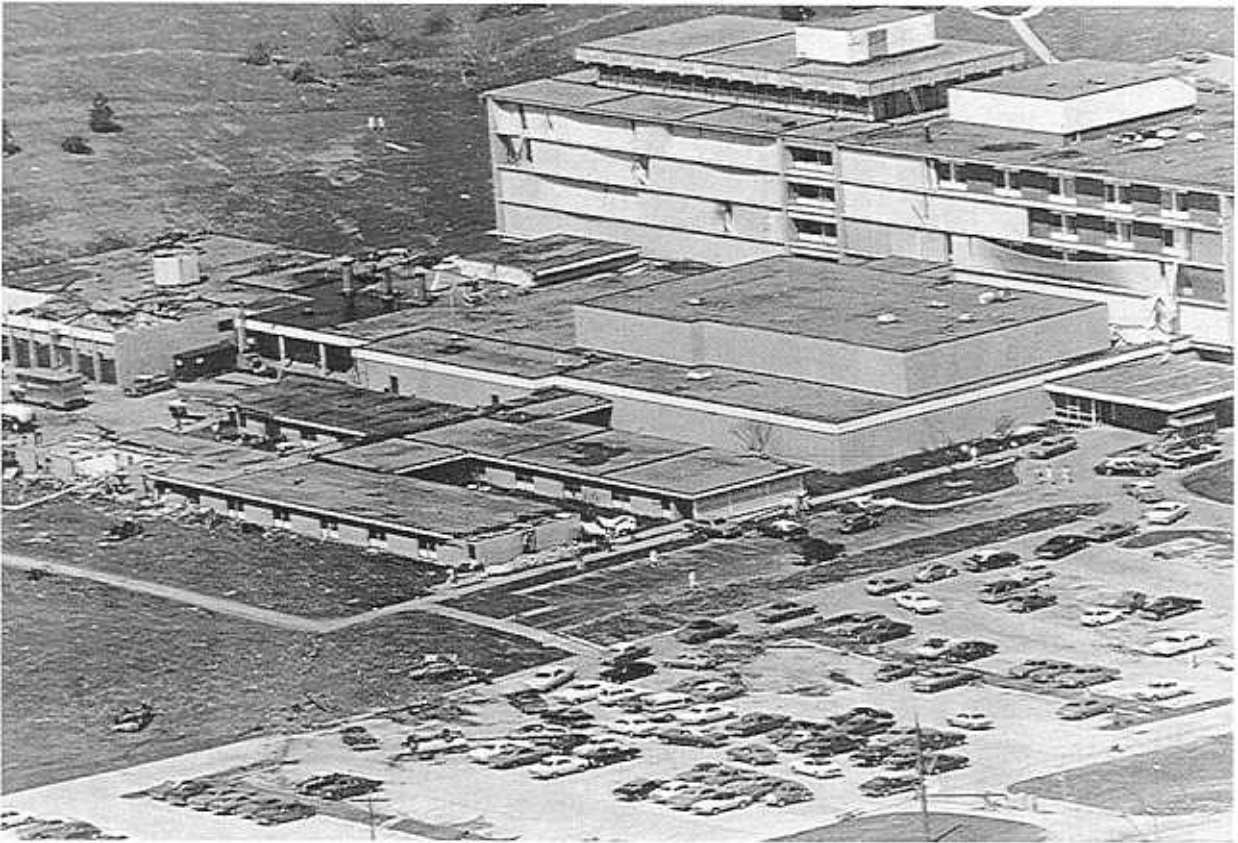
FIGURE 14. BERGAN MERCY HOSPITAL IN OMAHA, NEBRASKA IS A FULLY
ENGINEERED BUILDING. The six-story wing sustained
the full force of a tornado on May 6, 1975, with
minimal damage.

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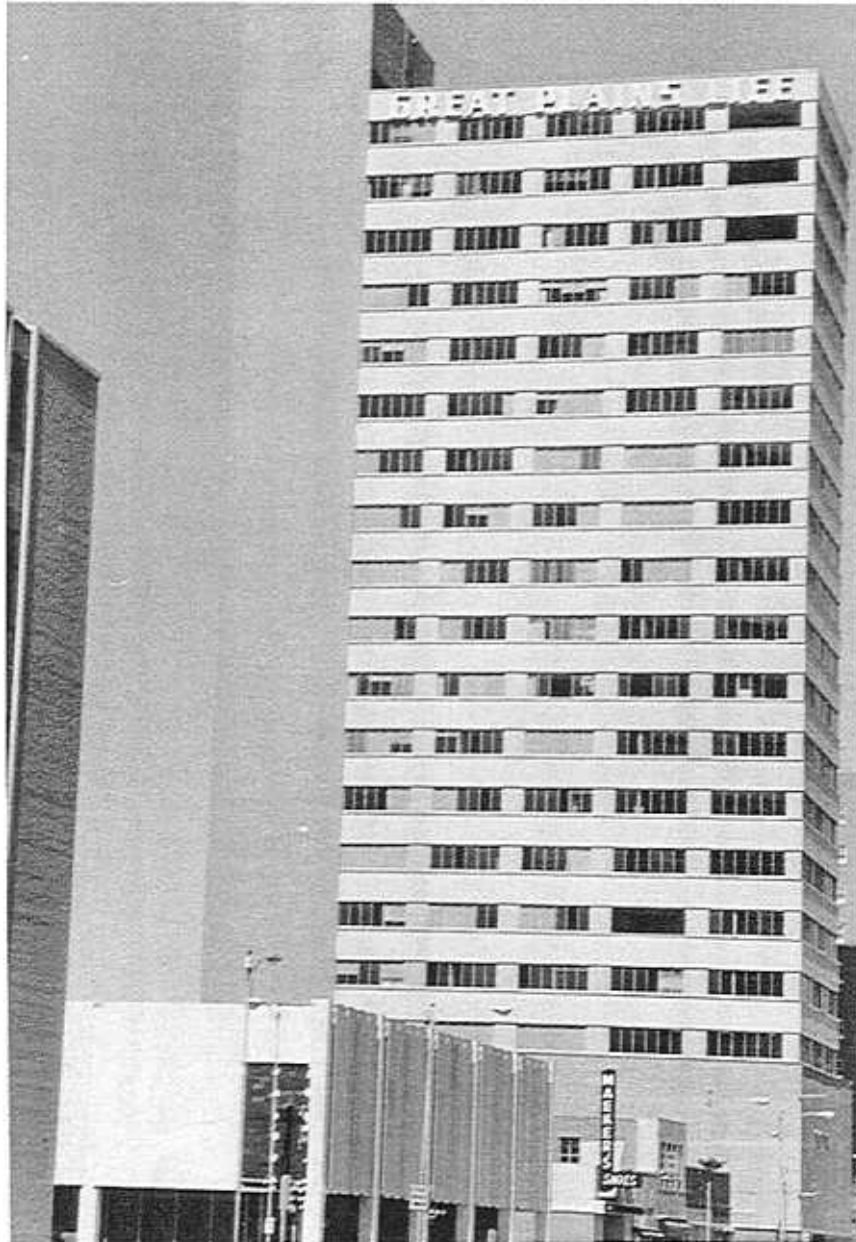
FIGURE 15. THE GREAT PLAINS LIFE BUILDING IN LUBBOCK, TEXAS WAS DAMAGED
BY WINDS ON MAY 11, 1970. Although the steel frame was per-
manently deformed, the fully engineered building has been
restored to useful service.

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FIGURE 16. THE FIRST NATIONAL BANK BUILDING IN LUBBOCK, TEXAS SUSTAINED
ONLY GLASS DAMAGE. This fully engineered building is located
only two blocks from the Great Plains Life Building.

is achieved. Windstorm events have revealed certain weaknesses in
these building systems. Several failure modes are characteristic of
this building classification. Detailed treatments of failure modes
in metal building systems are outlined in a report by Sanger and
Minor (1971). Generally, failures in overhead doors allow winds to
enter the building, producing internal pressures and the large pres-
sures across wall and roof components illustrated in Figure 4. Many
metal building manufacturers design the overhead doors in conjunction
with the balance of the building and avoid this weakness. Other manu-
facturers subcontract the overhead door design and installation, and,.
by yielding this responsibility, often obtain a door which is not as
strong as the balance of the building. The door, then, represents a
weak point insofar as wind resistance is concerned. Figure 17 illus-
trates the character of damage typified by this type of failure.
Buildings in this classification often appear to have "exploded" be-
cause of the wind-induced pressure increase inside the building (Fig.
4). Another common failure mode for metal buildings is loss of
cladding along corners, eaves, and ridges (Fig. 18), the location
of localized outward-acting pressures. Both of these failure modes
commonly occur at relatively low windspeeds, e.g. less than 125 mph
(55.9 m/s).

3. Marginally Engineered Buildings

The largest single contributor to losses in windstorms is
caused by failures of a large number of buildings which may be clas-
sified as "marginally" engineered. Commercial buildings, light in-
dustrial buildings, schools, and certain types of motels and apart-
ments which are built with some combination of masonry, light steel
framing, open-web steel joists, wood framing, wood rafters, and
concrete comprise this group of structures. The term "marginally"
engineered comes about because while a degree of engineered attention
is given to designs, this attention is limited in extent, relative to
the amount of attention given to a fully engineered building. The
engineering process tends to become conventional; i.e., once a struc-
ture of a given type has been built in a certain area, similar struc-
tures of the same type are erected without repeating the detailed
calculations and inspections attendant to good design and construc-
tion practices.

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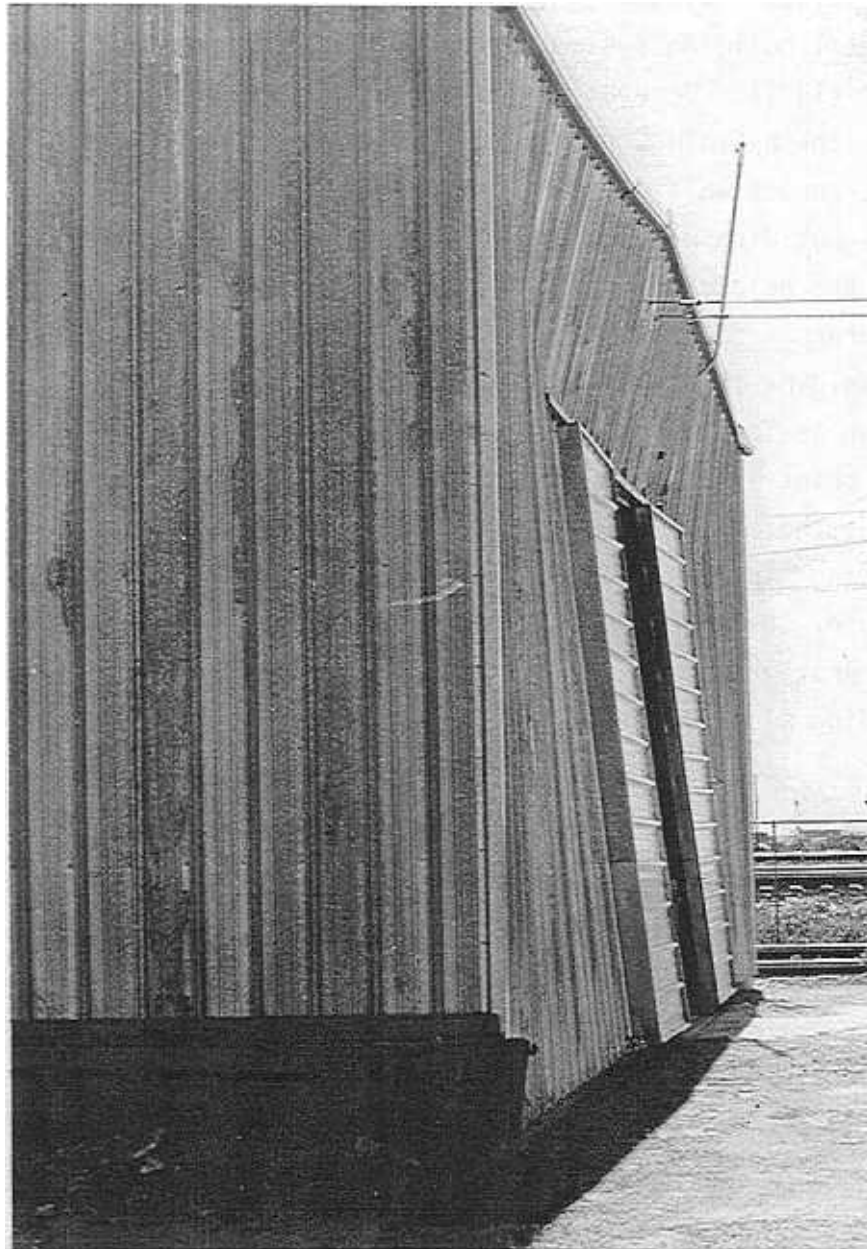
FIGURE 17. METAL BUILDING SYSTEMS MAY SUSTAIN FAILURE BECAUSE OF A WEAK
COMPONENT. Overhead doors or the bracing in windward walls
sometimes are the failure initiation points.

FIGURE 18. METAL BUILDING SYSTEMS EXPERIENCE LOSS OF CLADDING
Local pressures along eaves and corners are re-
flected in damage pattern.

Buildings of this type which contain masonry are most often major contributors to damage. Three types of buildings containing masonry are common: buildings in which the roof system is supported by the walls, making the walls "loadbearing," buildings with light steel framing (often steel pipes and light "I" beams) with masonry walls between columns called "fill-in walls," and non-loadbearing exterior walls. Wind-induced forces commonly push the masonry walls inward or outward, depending upon wind approach direction and the character of windward wall openings. In the case of loadbearing masonry, the roof system falls downward when the walls collapse. In the case of masonry fill-in walls, and non-loadbearing exterior walls, wall collapse does not produce frame collapse, but the contents of the affected building are destroyed, thus compounding the value of damage. Windspeeds as low as 100 mph (44.7 m/s) can cause failures of this type. Figures 19 and 20 illustrate failures in loadbearing masonry and masonry fill-in walls. While these failures are illustrative of severe damage and give outward appearances of extreme forces and windspeeds, most often they are induced by relatively nominal winds, e.g. 125 mph (55.9 m/s) or less.

Motel and apartment units which are framed principally with wood usually receive some engineering attention. Again, however, this attention is marginal and tends to leave the buildings vulnerable to wind-induced forces. Common are roofs removed because of inadequate connection to walls, and roof failures brought about by "overhangs" over walkways (e.g. along the pathway in front of rooms) being lifted when wind-induced pressures build underneath. In these failures, damage appears to be severe and is usually described as "total destruction," yet the windspeeds causing the damage are nominal, e.g. 125 mph (55.9 m/s) or less. Figure 21 illustrates common failures in this type of structure.

Commercial, school, and motel type structures may also be built with other combinations of steel, masonry, wood, and concrete. Construction using unique combinations of these building materials are common. While combinations of these materials can be used effectively in engineered designs, often these hybrids are carelessly assembled

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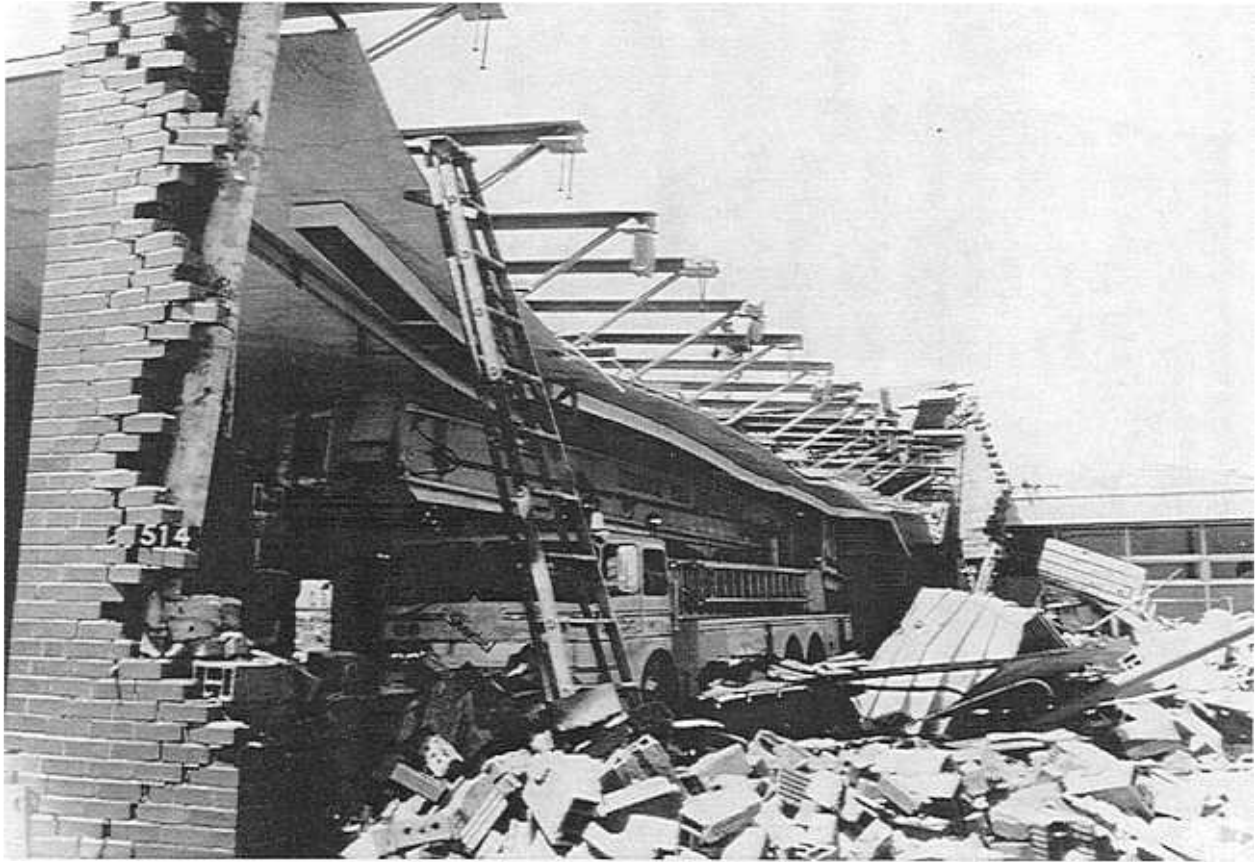
FIGURE 19. LOADBEARING MASONRY WALL FAILED OUTWARD, PERMITTING ROOF TO FALL ONTO FIRE TRUCK. This failure was at the Central Fire Station in Lubbock, Texas.

FIGURE   MASONRY FIL   WAL FAILURE. Concrete block walls
          led space between steel

FIGURE 21. ROOFS WHICH EXTEND OVER WALKWAYS CAN BE FAILURE INITIATION POINTS. This motel in Lubbock, Texas lost its roof in this manner in May 1970.

and provide only minimal resistance to wind-induced forces. An example of a structure which employed a unique combination of steel framing, loadbearing masonry, timber roof components, and fill-in walls is illustrated in Figure 22.

4. Non-Engineered Buildings

A large class of buildings receives no engineering attention at all. These buildings are single and multifamily residences, certain apartment units, and many small commercial type buildings. If the marginally engineered buildings discussed above are vulnerable to wind-induced forces, then non-engineered buildings are more vulnerable. Consisting largely of wood frame construction, these buildings are, generally, poorly designed and constructed to resist lateral and uplift forces generated by the wind. Roof to wall connections, wall to foundation connections, resistance to lateral or "wracking" loads, and inadequate overall structural integrity typify these buildings. Windspeeds of hurricane velocity (73 mph; 33 m/s) represent the threshold of damage for these buildings, and total destruction may occur when winds reach 125 mph (55.9 m/s).

A common, damage related inference is to conclude that extreme winds [200 mph (89.4 m/s) or more] must have caused residential damage if the house is totally removed from its foundation. Winds not much larger than 100 mph (44.7 m/s) can move a house from its foundation if it is poorly constructed or poorly anchored. Rural houses and houses in certain cities where building codes are non-existent or not enforced have proved to be particularly vulnerable to destruction at relatively small windspeeds. Examples of poor construction practice, including inadequate anchorages, are illustrated in Figure 23; more detailed treatments of the performance of housing are advanced in Section VI.

FIGURE 22. BUILDINGS COMPOSED OF STEEL, WOOD, AND MASONRY ARE OFTEN
"MARGINALLY ENGINEERED." Hybrids such as this building
in Lubbock are vulnerable to wind damage.

FIGURE 23. HOUSING DAMAGE CAN BE TRACED TO POOR CONSTRUCTION PRACTICE.
Inadequate roof anchorages (top) and foundation anchorages
(bottom) resulted in damage to houses in Omaha (Nebraska)
and Burnet (Texas).

IV. TORNADIC WINDSPEEDS

A. Importance to the Engineer

In recent years estimates of the upper limit of tornadic windspeeds have fallen from about 500 mph (224 m/s) (Waite and Lamoureux, 1969; OEP, 1972) to a value in the 250-300 mph (112-134 m/s) range (Davies-Jones and Kessler, 1974; Mehta et al.,1976). This dramatic reduction in maximum tornadic windspeed has profound implications for the engineer. Structures can be designed, within economic reason, to be tornado-proof if a windspeed on the order of 300 mph (134 m/s) is employed as a limiting value. Such structures have been designed and constructed for use in the nuclear industry and for use as tornado shelters. Perhaps more important, however, are implications for conventional construction. The limiting value of 300 mph (134 m/s) or less and the observation that only a very small percentage of all tornadoes approach this limiting value mean that tornado resistant structures can be designed and built for many more common applications (Minor, 1976). Some recent work has suggested that a design approach based upon economic considerations of wind-resistant construction, including consideration of tornado occurrence and severity probabilities, might be generally applicable (Lambert, Mehta, and Minor, 1975).

Modern estimates of windspeeds in tornadoes have been established through coordinated efforts of engineers and meteorologists. Meteorologists develop estimates of tornadic windspeeds through modeling, laboratory work, and photogrammetric evaluations (Golden, 1976; Lewellen, 1976; Davies-Jones, 1976; Fujita, 1975, 1976). Engineers rely principally upon calculations of forces that produce damage to estimate tornadic windspeeds. This approach requires understanding of building failure modes and air flows around structures such as those advanced in Section III. Only efforts of engineers which employ the latter approach are treated in this report

B. Calculations of Tornadic Windspeeds

The literature contains numerous presentations of somewhat similar procedures for assessing the response of structures to strong gusty

winds. Representative of these procedures are a classic paper by
Davenport (1961), an experimental treatment by Smart, Stevens, and
Joubert (1967), and a paper by Handa and Clarkson (1968). In these
generalized treatments of the interaction of gusty winds with elas-
tically responding structures, it is pointed out that structural re-
sponse is manifested in two response functions: (1) a function in
which the classic $\frac{1}{2} \rho \, C_D \, V^2$ term relates to the drag force, described
as the "drag"term, and (2) a function in which the reaction of the
structure is associated with the acceleration of the wind, described
as the "acceleration" term. Further, it is pointed out that the
coefficients of drag C_D in the drag term can be associated with a mean
windspeed value, if the wind turbulence and structural response are
governed by probabilistic processes which are stationary (i.e. indepen-
dent of the origin of time and of the duration of the wind record).
Finally, it is observed that the acceleration term becomes increasingly
more important as wind environments are encountered which possess very
rapid changes in wind velocity relative to fundamental frequencies of
vibration of the structure.

These presentations of procedures for characterizing wind-structure
interaction phenomena are useful to the present study in that they pro-
vide a perspective for the presentation of ensuing windspeed calculations.
The literature is quick to point out, however, the limitations of these
procedures in application to tornadic and other extremely turbulent wind
conditions. Davenport(1961) quotes Fedyayevsky and Belotserkovsky (1954),
who treated aerodynamic forces acting on buildings in squalls, as suggest-
ing that the fluid acceleration term may be at least as important as the
drag term in some instances. In any event, tornadic windfield conditions
by their very nature would seem to violate the assumptions of stationary
processes which are fundamental to formulations of the response of struc-
tures to wind. While some of these concerns are valid, wind damage docum-
entations suggest that the structural systems of interest from an analysis
viewpoint tend to be structural components (e.g., walls, wall panels, roof
panels)rather than complete structures. Hence, the formulations which ad-
dress complete structural systems -- as charaterized by coefficients of drag,

total mass, and overall dynamic characteristics -- are not directly applicable to many of the structures of interest.

Hence, it seems that the wind engineer in assessing tornadic windspeeds using the current state of the art is faced with a dilemma. On the one hand, he has to acknowledge the possible contributions to structural response by the acceleration term in the dynamic formulations. On the other hand, he may have justification for neglecting this contribution because the fundamental natural frequencies of the structural components of interest may be so large (relative to the frequency content of the turbulent wind) as to permit neglecting of this component. In either event, he has to work with very large unknowns associated with the basic character of the windfield and with the validity of local pressure coefficients (as opposed to overall drag coefficients) applicable to structural components.

The wind engineer is faced with making windspeed assessments, notwithstanding the limitations imposed upon him by the state of the art. In approaching the problem he must acknowledge these limitations while at the same time doing the best he can with the procedures available to him. Furthermore, he must temper the calculations made under these conditions with his own judgment and experience. In so doing, he can place his own judiciously considered estimates of accuracy on the results.

C. Engineering Estimates of Tornadic Windspeeds

Mehta (1976) and Mehta et al. (1976) have advanced the state of the art of windspeed analysis procedures through consideration of engineered structures in the intense tornadoes of April 3-4, 1974 and through the development of credence levels that can be associated with windspeed estimates. The basic approach uses only the drag term within the formulations discussed above; possible acceleration effects are considered in establishing a "credence level" for each estimate.

1. Basic Equation

Principles of mechanics permit the structural engineer to determine the pressure p (in psf) that will cause a given structure or structural component to fail. These procedures entail the use

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of structural analysis techniques that are used in the design of buildings with various materials and framing schemes. The procedures constitute the practice of structural engineering and will not be addressed here.

Once a uniform wind pressure p that can damage a structure or a building component is obtained, the windspeed that produces this pressure can be calculated using expressions for basic wind pressure as defined in the ASCE Task Committee Report "Wind Forces on Structures" published by the American Society of Civil Engineers in Transactions, ASCE (1961). The basic wind pressure expression is:

$$p = 0.00256 \ V^2 \ C_d \tag{1}$$

Where

    p is the wind pressure in psf

    V is the windspeed in mph

    C_d is a drag, shape or pressure coefficient.

The constant 0.00256 is based on a unit weight of air equal to 0.07651 pcf (1.226 kgf/m^3) at 15°C and 760 mm of mercury. Values of the drag or pressure coefficients C_d can be obtained from the ASCE Task Committee Report (1961), from American National Standards Institute Standard A58.1 (ANSI, 1972), or from other technical literature.

The ANSI A58.1 standard defines three types of pressure coefficients:

    External pressure coefficient, C_p

    Internal pressure coefficient, C_{pi}

    Net pressure coefficient, C_f.

External pressure coefficients are applicable for external wind pressures acting on enclosed buildings. The equation for externally-acting wind pressure is:

$$p = 0.00256 \ V^2 \ (C_p) \tag{2}$$

If the building has windows and doors or other openings so that the wind can gain entry inside the building, internal pressures

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act on the walls and roof in addition to the external pressures. The equation for combined external and internal wind pressures acting on a building component is:

$$p = 0.00256 \ V^2 \ (C_p - C_{pi})$$

Careful attention must be paid to the signs of the internal pressure coefficients C_{pi}, because they are a function of wind direction and opening location.

Net pressure coefficients are used for structures such as chimneys and towers. The wind pressure is the net horizontal pressure and is obtained by the equation:

$$p = 0.00256 \ V^2 \ (C_f)$$

With the knowledge of wind pressure p which causes failure calculated from structural mechanics procedures, and with appropriate pressure coefficients determined from the literature, the threshold windspeed V which causes failure can be calculated utilizing the above equations.

It should be recognized that a number of assumptions are made in the simple analytical procedure described above. These assumptions cause variations in the degree of reliability of the calculated windspeeds. Variability in windspeed calculations introduced by these assumptions and attendant "credence levels" assigned to windspeed estimates because of this variability are discussed in the next section.

2. Credence Levels

There exists a degree of uncertainty in the analytical procedure described above. Uncertainties in windspeed estimates can be judged if component parts of the analytical procedures are examined separately. Important component parts of windspeed calculation procedures are: (1) definition of structural system, (2) definition of material strengths and construction practices which affect performance, (3) definition of gust sensitivity, (4) selection of pressure coefficient values, and (5) establishing location of windspeed estimate with respect to failure origin point. Uncertainties within each component part are discussed below.

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Uncertainties in each component part of the analysis process are examined from the point of view of credence level lent to calculated windspeeds. Subjectively derived credence levels entitled "good," "acceptable," and "questionable" are assigned to each component part. Determinations of windspeed estimates with numerical confidence levels are not possible with present knowledge.

° Definition of Structural System

The confidence with which windspeeds can be estimated from structural failures depends on the degree of complexity of the structural system. Simple and uncluttered structural systems yield more reliable windspeed estimates than more complex structural systems because the mathematical definitions of simple structures are direct and straightforward. A scheme for classifying structural systems has been proposed as follows: (1) free-standing structures, (2) "clean" structures, (3) framed structures, and (4) buildings (Mehta et al., 1976).

Free-standing structures such as signs (Fig. 24) and chimneys, and "clean" structures such as bridge beams, TV antennae, and water towers (Fig. 25) are readily analyzed with respect to damaging windspeeds. These types of structures provide good, reliable windspeed estimates.

Framed structures such as industrial metal buildings (Fig. 26) and conventional buildings (Fig. 27) can be analyzed to estimate damaging windspeed; however, careful evaluation of the damaging mechanism is necessary to gain reliable windspeed estimates. Conventional buildings generally resist windloads through relatively complex interactions among various components of the building, rather than by action of the frame alone. The complete collapse of an entire building is a difficult failure to analyze because the contributions of various building components in resisting windloads are not easily established. However, failures of conventional building components, such as roofs and solid exterior walls, can be analyzed and used to estimate windspeeds with a relatively high degree of confidence.

Residential structures and rural buildings (Fig. 28) are difficult to analyze. Connection and anchorage details in these buildings are, generally, not standard and there are wide variations

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FIGURE 24. FREE-STANDING STRUCTURES PROVIDE THE BEST OPPORTUNITY FOR ANALYSIS OF WINDSPEED. This sign in McComb, Mississippi provided windspeed estimates for a tornado which occurred in January 1975.

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FIGURE 25. A "CLEAN" STRUCTURE SUCH AS A WATER TOWER CAN PROVIDE GOOD WINDSPEED
ESTIMATES. This water tower in Brandenburg, Kentucky was very close
to the tornado path on April 3, 1974.

FIGURE 26. A FRAMED STRUCTURE CAN PROVIDE RELIABLE WINDSPEED ESTIMATES IF CARE IS
TAKEN IN ANALYSIS. This soft-drink warehouse in Lubbock, Texas could
have failed at windspeeds as low as 80 mph (35.8 m/s).

FIGURE 27. COMPONENTS OF CONVENTIONAL BUILDINGS CAN BE USED IN WINDSPEED ANALYSES. The roof of Xenia High School provided windspeed estimates for the Xenia, Ohio Tornado of April 3, 1974

FIGURE 28.   HOUSING CAN PROVIDE ROUGH ESTIMATES OF WINDSPEEDS.
This house in Brandenburg, Kentucky was moved by
tornadic winds in the 80-120 mph (36-67 m/s) range.

in material strengths, construction methods, and design approaches--
often within the same structure (See Section VI, Housing).

Items such as fertilizer tanks, school buses, water heaters,
and truck trailers that have been moved by the wind are often utilized
to estimate windspeeds in tornado incidents. Windspeed estimates
based on missiles are rated "questionable" because relatively little
is known about flight characteristics of odd-shaped missiles, such
as the missile shown in Figure 29.

The discussion of difficulties in defining structural sys-
tems suggests that different types of structures can be considered
to provide different credence levels for windspeed calculations as
follows:

    °Good - free-standing structures, 'clean' structures
    °Acceptable - framed structures, conventional buildings
    °Questionable - residences, rural buildings, missiles

       °Definition of Material Strength and Construction
       Practices which Affect Performance

Failure strengths of materials such as steel, concrete,
masonry, and timber vary. Variations in strengths are much larger
in materials manufactured on site, such as concrete and masonry,
than in materials which are manufactured in plants, such as steel.
Timber strengths vary considerably because strengths of wood depend
upon type of wood and on the environment in which the wood was grown.
Glass has a wide range of strengths because glass strength is sensi-
tive to the rate of loading and to imperfections and scratches which
may be present on glass surfaces.

Construction practices can vary considerably with time
and place. This observation was made in the evaluation of twelve
school buildings which were damaged in the April 3, 1974 tornado out-
break in Indiana, Ohio, and Kentucky (Croghan, 1978). The school
buildings were constructed in the time span from 1930 to 1960. In
general, steel structures and steel connections were found to reflect
more consistent construction practice than concrete and masonry
structures.

Credence levels for calculated windspeeds can be based on
definitions of material strengths and construction practices as follows:

FIGURE 29.   ODD-SHAPED MISSILES PROVIDE THE LEAST RELIABLE BASIS FOR
DETERMINING TORNADIC WINDSPEEDS.   This trailer tumbled
600 ft (183 m) or more in the Hubbard, Texas Tornado of
March 10, 1973.

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°Good - steel, steel connections.

°Acceptable - concrete, masonry, timber, precast concrete, engineered connections.

°Questionable - glass, nailed connections.

° Definition of Gust Sensitivity

Procedures employed to determine the response of structures to strong gusty winds as advanced by Davenport (1961) are discussed in Paragraph IV.B. It was noted that the "acceleration term" of the basic formulation becomes increasingly important relative to the "drag term" as wind environments are encountered which possess very rapid changes in wind velocity (gustiness), relative to fundamental frequencies of vibration of the structure. Windspeed estimates obtained from damaged structures with low fundamental frequencies of vibration (e.g. flagpoles) are not reliable because there may be significant contributions by the acceleration term to the structural response. The current knowledge of gustiness in tornadic windfields is not sufficiently advanced to permit accurate determinations of the contributions of acceleration terms to structural response.

Most low-rise, conventional structures, and, particularly, most structural components (e.g. walls, wall panels, roof panels) have relatively large fundamental frequencies of vibration, which are not sensitive to the acceleration term in structural response formulations. Windspeed estimates obtained in examples presented in Section VI.E do not include the acceleration term but are, nonetheless, considered dependable for low-rise structures and certain structural components.

Electric power transmission towers and above ground utility lines are also sensitive to wind gustiness because the power lines are gust sensitive. Hence, damaged transmission towers or utility poles which have experienced substantial loading through power lines are not likely to provide reliable windspeed estimates.

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Credence levels for calculated windspeeds which involve
gust sensitivity formulations can be listed as follows:

°Good - Rigid structures with high fundamental frequencies
        of vibration, including components of conventional
        buildings

°Acceptable - Certain frame buildings

°Questionable - Flexible, tall, slender structures (flag-
        poles, light standards) with low funda-
        mental frequencies of vibration

Selection of Pressure Coefficients Values

The drag term in structural response formulations referred
to in the previous paragraph represents the wind pressure acting on a
structure or a building component. The wind pressure is a function of
the square of the windspeed and a shape, drag, or pressure coefficient.
These coefficients are generally associated with mean windspeed values.
These coefficients are referred to as net pressure coefficients when
total wind pressures on an entire structure are considered, and as
external, internal, and localized pressure coefficients when wind
pressure on building components are considered (ANSI, 1972).

It is recognized that uncertainties exist in applying the
values of pressure coefficients found in the literature to specific
analysis situations. The two most significant uncertainties come about
because (1) available pressure coefficient values are obtained from
wind tunnel tests and may not reflect the effects of the turbulent
boundary layer which is present in the field, and (2) pressure co-
efficient values sometimes represent "envelope" or maximum values for
a given component for all angles of wind incidence.

The intensity of wind turbulence can change pressure co-
efficient values considerably. In a wind tunnel study conducted at
Washington·State University (Crowe et al., 1974), it was found that pressure
coefficient values on side and leeward walls varied by 20 percent
when the turbulence intensity in the free wind stream was changed
from 0.5 percent to 8 percent. The extent of variability in differ-
ent types of pressure coefficients is being studied, and accurate
data are not available at this time.

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Values of pressure coefficients presented in the general literature sometimes represent maximum or "envelope" values for all angles of wind incidence. Actual pressure coefficient values are likely to be smaller than the envelope values except when the actual wind incidence angle corresponds to the angle which produces the maximum pressure coefficient value. Indications are that net pressure coefficient values (drag coefficients) are least affected by changes in angle of wind incidence, while the local pressure coefficient values are most affected by changes in angle of wind incidence.

The pressure coefficient values presented in ANSI A58.1 (ANSI, 1972) represent the best available knowledge at this time. The impact of the above mentioned variations in pressure coefficient values on windspeed calculations is minimized because windspeed is inversely proportional to the square root of the pressure coefficient. Thus, a variation of 20 percent in the value of a pressure coefficient changes the windspeed by about 10 percent.

In view of the above discussions on the selection of pressure coefficient values, credence levels of calculated windspeeds relative to types of pressure coefficients can be advanced as follows:

°Good - Net pressure coefficients

°Acceptable - External and internal pressure coefficients

°Questionable - Localized pressure coefficients

° <u>Establishing Location of Windspeed Estimate</u>

Engineering analysis of a damaged structure provides a ground-level windspeed estimate at the point of damage. Extrapolation of windspeed estimates to locations other than the points of failure is a questionable practice. Uncertainty in extrapolation of the windspeed estimate exists because, generally, it is difficult to ascertain which part of the tornado windfield -- front, side, or back -- caused the damage. In addition, the variation in tornado windspeed with tornado radius has not been established in sufficient detail as yet to allow such extrapolation with any degree of reliability. In analyzing the Worcester County, Massachusetts tornado incident, Booker (1953) estimated a peripheral tornadic windspeed of approximately 350 mph (156 m/s). The extrapolated windspeed estimate of 350 mph (156 m/s) was based

upon an assumed wind velocity vs. radius profile. Because the reported value was for a point for which direct calculations were not made, the estimate is questionable.

Credence levels for calculated windspeeds, with respect to location, can be assigned as follows:

°Good - At the point of failure

°Acceptable - Near the point of failure

°Questionable - Extrapolated to points away from the
point of failure.

D.   Summary of Windspeed Estimates from the Literature

Windspeed estimates are recorded in the literature for numerous tornado incidents. Engineering analyses of failed structures provide many of these estimates. Several windspeed estimates developed from engineering analyses have been examined in terms of credence levels defined above and summarized in Table I. The investigated windspeed estimate cases are shown in Table II. Examination of Table II shows that many of the windspeed estimate cases show "good" and "acceptable" credence levels for calculated windspeeds. For these cases, the wind-speed estimate values can be considered reliable. However, several of the windspeed estimate cases have a "questionable" credence level entered in one or more entries for calculated windspeeds. In the cases of "questionable" credence level, the windspeed estimate values should be viewed with caution.

A review of Table II indicates that each windspeed estimate in excess of 200 mph (89 m/s) contains a "questionable" credence level rating in at least one entry, except one. This one estimate relates to windspeed calculations utilizing displaced tombstones (grave markers) in the tornado event at Brandenburg, Kentucky on April 3, 1974 (Shana-han, 1976). Thirteen displaced tombstones were analyzed by Shanahan. Eight tombstones yielded windspeed estimates of 100 to 150 mph (45-67 m/s), three tombstones provided windspeed values of 180 to 230 mph (80-103 m/s), and two tombstones yielded windspeed estimates of 270 mph (121 m/s) and 325 mph (145 m/s), respectively. The two tombstones

TABLE I

CREDENCE LEVELS FOR WINDSPEED CALCULATIONS

Component of Windspeed Calculation Procedure	Credence Level		
	Good	Acceptable	Questionable
Definition of Structural System	°free-standing structures °"clean" structures	°framed structures °conventional bldgs.	°residences °rural bldgs. °missiles
2. Definition of Material Strengths	°steel °steel connections	°concrete °masonry °timber °precast concrete °engineered connections	°glass °nailed connections
3. Definition of Gust Sensitivity	°rigid structures (e.g. low-rise reinforced concrete)	°non-rigid structures (e.g. certain framed bldgs.)	°flexible structures (e.g. flagpoles)
4 Selection of Pressure Coefficient Values	°net pressure coefficients	°external and internal pressure coefficients (C_p, C_{pi})	°local pressure coefficients
5. Establishing Location of Windspeed Estimate	°at point of failure	°near point of failure	°points away from point of failure

TABLE II

CREDENCE LEVELS FOR ESTIMATED WINDSPEEDS FOUND IN LITERATURE

Tornado Incident	Reference	Item	Cal. Wind Speed Est mph (m/s)	Credence Level					Remarks
				Structural System	Material Strengths	Gust Sensitivity	Pressure Coefficients	Location	
Chatenay, France 1839	Lalanne (1839)	Masonry Wall	168 (75)	-	-				Sufficient details are not known.
Novska,Yug. 1892	Mohorovicic (1892)	25,000 lb Locomotive	223 (100)	Questionable					Sufficient details are not known.
Italy 1930	Puppo and Longo (1934)	Transmission Towers	145-298 (65-133)	Questionable	Good	Questionable		Good	Wide variation in windspeed is due to different assumptions in failure mode.
Worcester, MA 1953	Booker (1953)	Transmission Tower	300-350 (134-156)	Good	Good	Questionable	Good	Questionable	Failure windspeed calculated 148-170 mph. Value of 350 mph is extrapolated.
Dallas, TX 1957	Segner (1960)	Masonry Walls	92-109 (41-49)	Acceptable	Acceptable	Good	Acceptable	Good	
		Roof	179-189 (80-84)	Acceptable	Questionable	Good	Acceptable	Good	Strength of nail connection is difficult to ascertain.
		Storage Tank	65 (29)	Good	Good	Good	Good	Good	
		Eight Freight Cars	83-217 (37-97)	Questionable		Good	Good	Good	Overturning of freight car on end is questionable.
		45-ft Sign	302 (135)	Questionable	Acceptable	Good	Good	Good	Author reports this value doubtful because of questionable sequence of failure.
		Truck Bed	123 (55)	Questionable		Good	Good	Good	Windspeed obtained from missile.
		Flagpole	189 (84)	Good	Good	Questionable	Good	Good	Structure is tall and slender.

TABLE II

CREDENCE LEVELS FOR ESTIMATED WINDSPEEDS FOUND IN LITERATURE (Cont'd.)

Tornado Incident		Item	Cal. Wind Speed Est mph (m/s)	Credence Level					Remarks
				Structural System	Material Strengths	Gust Sensitivity	Pressure Coefficients	Location	
Lubbock, TX 1970	Mehta McDonald Minor (1971)	Fertilizer Tank	183 (82)	Questionable	-	Good	Good	Good	Windspeed obtained from missile
		Frame Structure	68 (30)	Acceptable	Good	Good	Acceptable	Good	
		Roof	75-100 (34-45)	Acceptable	Acceptable	Good	Acceptable	Good	
		Light Standard	75-126 (34-56)	Good	Good	Questionable	Good	Good	Structure is tall and slender.
		Masonry Wall	75 (34)	Acceptable	Acceptable	Good	Acceptable	Good	
		Bridge Beams	65-115 (29-51)	Good	Acceptable	Good	Good	Good	
Lubbock, TX 1970	Reed (1970)	Glass in 20-Story Building	179 (80) @ 140 ft; 95 (42) @ 30 ft	Acceptable	Questionable	Good	Acceptable	Questionable	Glass material strength vary drastically. Also 95 mph at 30 ft is extrapolated value.
Wisconsin 1974	Blechman Anderson Lovell (1974)	Steel Fence Post	358 (160)	Questionable	Good	Questionable	Good	Good	Value of 358 mph is unreasonably high because contribution of wire fence is neglected and possibility of debris impact is not considered.
Windsor, Canada (1974)	Miranda (1975)	Masonry Wall	45 (20)	Acceptable	Acceptable	Good	Acceptable	Good	
Monticello, IN 1974	Mehta (1976) Costello (1975)	Railroad Bridge Beams	150 (67) 190 (85)	Good	Good	Good	Good	Good	Differing angle of attack of wind gives two different windspeeds.
Xenia, OH 1974	Almuti (1974)	Utility Pole	180 (80)	Good	Acceptable	Questionable	Good	Good	Load on utility lines is not known.
		Metal Siding	176 (79)	Acceptable	Acceptable	Questionable	Acceptable	Good	Metal siding could vibrate amplifying gust effect.

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TABLE II

CREDENCE LEVELS FOR ESTIMATED WINDSPEEDS FOUND IN LITERATURE (Cont'd.)

Tornado Incident	Reference	Item	Cal. Wind Speed Est mph (m/s)	Credence Level					Remarks
				Structural System	Material Strengths	Gust Sensitivity	Pressure Coefficients	Location	
April 3-4, 1974	Mehta Minor McDonald (1976)	Masonry Chimney	133 (59)	Good	Acceptable	Good	Good	Good	
		Monument	159 (71)	Good	-	Good	Good	Good	Stone monument collapsed by overturning, no material strength involved.
		Masonry Wall	135 (60)	Acceptable	Acceptable	Good	Acceptable	Good	
		Roof Beams	138-187 (62-84)	Acceptable	Acceptable	Good	Questionable	Good	Localized pressure coefficients used.
		Truck Trailers	145 (65)	Questionable		Good	Acceptable	Good	Windspeed obtained from missile.
April 3-4, 1974	Croghan (1978)	Several Masonry Chimneys	88-167 (39-75)	Acceptable	Acceptable	Good	Good	Good	The reference contains approximately fifty calculations for twelve separate school buildings. Wide range of windspeed is because of different chimneys.
		Several Masonry Walls	66-188 (30-84)	Acceptable	Acceptable	Good	Acceptable	Good	
		Roofs	76-178 (34-80)	Acceptable	Acceptable	Good	Questionable	Good	Localized pressure coefficients used.
Brandenburg, KY, April 3, 1974	Shanahan (1976)	Thirteen Tombstones	108-325 (48-145)	Good		Good	Good	Good	Questionable assumptions in analysis method (see text).

which produce the highest windspeed estimates were assumed to have overturned on end because they came to rest on their narrow sides. While these tombstones are "clean" structures and, therefore, have "good" credence level ratings in each component part of the analysis, the assumed failure mode requires wind forces to act exclusively on the narrow side of the tombstone. This assumption seems questionable in view of the fact that the failure mode for other stones was such that wind forces acted on the wide side of the tombstones. This assessment of the situation in the cemetary suggests that windspeed estimates of 270 mph (121 m/s) and 325 mph (145 m/s) are questionable. Shanahan did not calculate windspeeds for undisplaced tombstones to establish upperbound windspeed estimates.

Windspeed estimates in Table II with "good" and "acceptable" ratings within each component part of the analysis all reflect windspeed values less than 200 mph (89 m/s). Assessments of windspeed estimates which exceed 200 mph (89 m/s) produce questionable ratings or other causes for questioning the calculation. These evaluations suggest that high levels of confidence can be associated with the statement that tornadic windspeeds approach 200 mph (89 m/s), but that statements that windspeed values exceed this number must be viewed with caution.

Evaluation of windspeed estimates in the manner shown in Table II places calculated values into perspective. In addition, the evaluation outlines for scientists and engineers the considerations which govern engineering analyses that must be used to gain dependable windspeed estimate values. This use of credence levels to evaluate the reliability of windspeed estimates represents an initial attempt. These procedures may be changed in the future as improved understandings of tornado-structure interaction phenomena become available.

E. Examples of Windspeed Estimates

Three examples of structural systems which can be used to estimate tornadic windspeeds are presented below. The examples were selected from several advanced by Mehta et al. (1976) as being illustrative of the three credence levels associated with the definition of structural systems.

1. <u>Penn-Central Railroad Bridge, Monticello, Indiana (Clean Structure)</u>.

A single-track, simple-span, dual-girder bridge carries the Penn-Central Railroad over the Tippecanoe River in the City of Monticello, Indiana. The tornado that struck Monticello on April 3, 1974 traveled from southwest to northeast across the center of town, and crossed the east-west oriented railroad bridge near its east end. Four spans were pushed sideways into the river (Fig. 30). Examination of plans furnished by the Penn-Central Transportation Company reveals that the simple spans were resting on steel pins and steel rollers (Fig. 31), with the pin and roller detail being of a character that would offer essentially no resistance to lateral load, other than through frictional forces. From a conventional design standpoint, these support details were adequate, as the frictional forces are substantial. Windspeed calculations are as follows:

(1) Total weight of a single span (from plans) is 223,300 lbs (101,290 kgf).

(2) Assumed steel on steel coefficient of friction μ is 0.35.

(3) Net pressure coefficient for rectangular bridge cross sections C_f is 1.3.

(4) Depth of plate girder is 10 ft (3 m).

(5) Span of plate girder is 105 ft (32 m).

(6) Force required to slide the span F is $F = \mu N = (0.35)(233,300) = 78,160$ lb (347 kN).

(7) Uniform wind pressure to develop force F is $p = F/[(10)(105)] = 74.4$ psf (3.6 kN/m^2); $74.4 = 0.00256 (1.3) V^2$ and $V = 150$ mph (67.1 m/s).

The foregoing windspeed must be considered to be a threshold windspeed as: (1) the analysis assumes that maximum winds act normal to the plate girders, and (2) the value corresponds to windspeeds necessary to start motion only. The value of 150 mph (67 m/s) seems reasonable as a probable maximum windspeed when compared to other damage analyses in the Monticello area (Mehta et al., 1975).

2. <u>Warner Junior High School Roof, Xenia, Ohio (Frame Structure)</u>.

This two-story frame structure sustained damage by uplifting of precast roof beams as shown in Fig. 32. The structure has enough venting area (through windows) to eliminate net forces due to atmospheric

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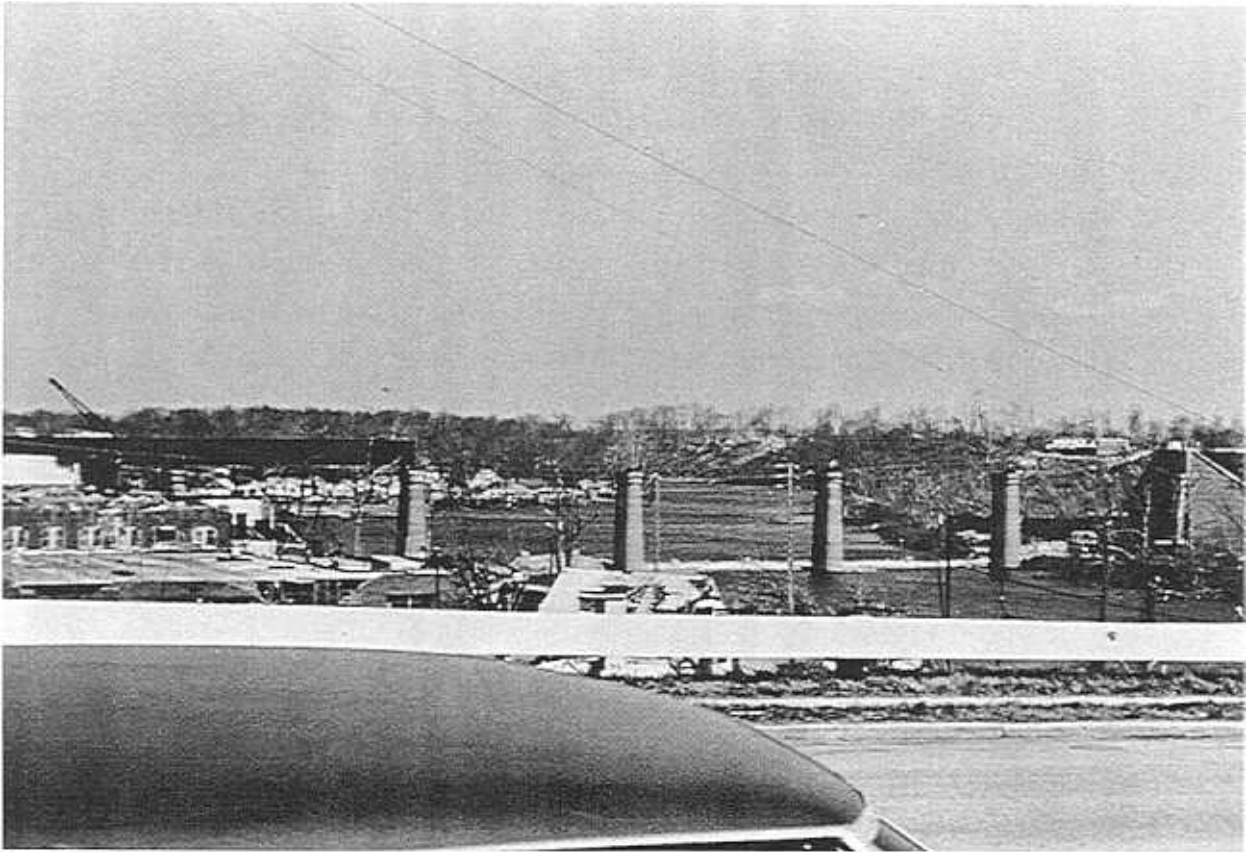
FIGURE 30. THIS "CLEAN" STRUCTURE WAS USED TO ESTIMATE WINDSPEEDS IN THE MONTICELLO, INDIANA TORNADO OF APRIL 3, 1974. The single track railroad bridge was pushed sideways into the river by winds estimated at 150 mph (67 m/s).

(a) Plan View of End Span

C.C. Girder

C Track

7'-0" (2.13 m)

105'-0" (32.0 m)
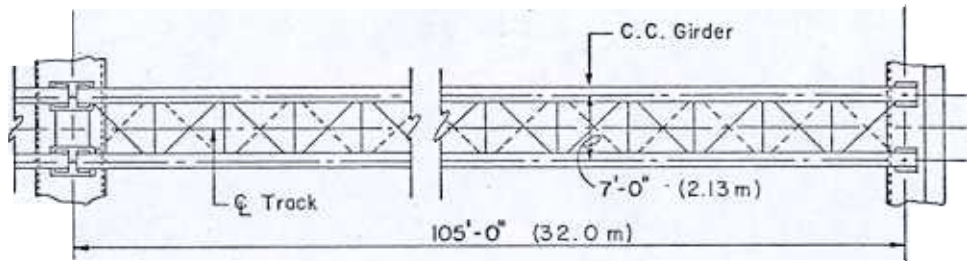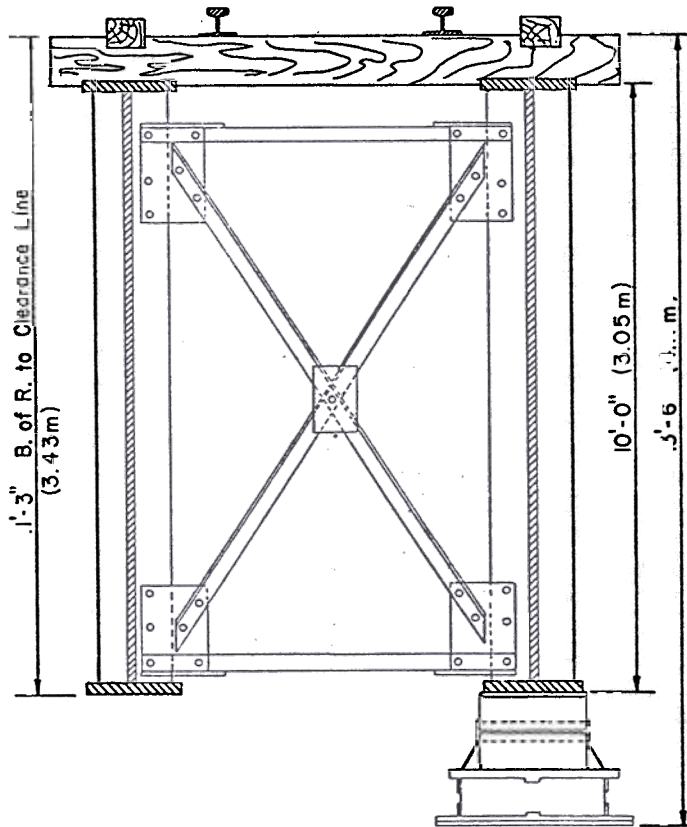
(b) Cross Section Through Girder

I'-3" B. of R. to Clearance Line (3.43m)

10'-0" (3.05 m)

.5'-6 .... m,
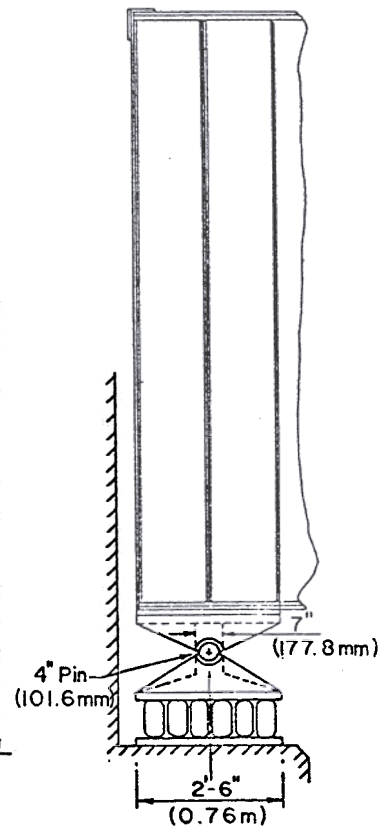
(c) Detail of Pin Assembly at Expansion End

4" Pin (101.6mm)

7" (177.8mm)

2'-6" (0.76 m)

FIGURE 31.   DETAIL OF BRIDGE STRUCTURE. The single-track, two-girder structure was restrained against lateral movement only by frictional forces on the pins.

FIGURE 32. UPLIFT FORCES ON THE ROOF COMPONENT OF THIS CONVENTIONAL BUILDING PROVIDED WINDSPEED ESTIMATES. Windspeeds in the range of 140-187 mph (626-836 m/s) lifted the concrete beams.

pressure change. Lifting of the precast beams could occur through aerodynamically induced pressures as air flows over the roof. The precast beams are "double tee" beams, 8 ft (2.4 m) wide and 12 in. (305 mm) deep; they span 26 ft (8 m) between supports and have a 2 ft (0.6 m) overhang. The beams were anchored by a 1/4 in. x 2 in. (6 mm x 51 mm) fillet weld along each leg of the beam at its supports. Since lifting of beams occurred only in a corner of the roof (the remaining beams were intact), it is possible to estimate a lower bound windspeed value that was experienced by the roof. The minimum width of the building w is 138 ft (42 m); thus, local pressure coefficients for roof corner and roof eave apply for a distance 13.8 ft (4.2 m) or 10 percent of w from the edge of the building, including the overhang area (ANSI, 1972). The breakage of window glass as shown in Fig. 32 dictates consideration of internal pressure as well as aerodynamically induced pressure. Wind pressures necessary to break the welds along the beams, either in the roof corner area or along the eave area, can be determined by taking moments about interior supports, as shown in Fig. 33.

Numerical calculations are as follows for the corner beam:

(1) Anchorage weld capacity = (0.25 x 0.707 x 4) (36,000) = 25,500 lb (11,570 kgf).

(2) Dead weight (including beam, insulation, and built-up roofing) is 47 x 8 = 376 lb/ft (560 kgf).

(3) Local pressure coefficient for flat roof corner is C_p = 5.0 acting on an area 13.8 ft x 13.8 ft (4.2 m x 4.2 m), including 2 ft (0.6 m) of the overhang.

(4) Pressure coefficient for eave of a roof is C_p = 2.4 acting on the remaining part of the corner beam.

Internal pressure coefficient for openings mainly in windward wall (broken window) is C_{pi} = 0.8 and it will act in conjunction with external pressure coefficients.

Taking moment about interior support as shown in Fig. 33 yields (25,500 x 26) + (376 x 28 x 14) - q[(8 x 13.8 x 21.1 x 5.8) + (8 x 14.2 x 7.1 x 3.2)] = 0; q = 50.3 psf (2.3 kN/m^2).

Utilizing Eq. 2, 50.3 = 0.00256 V^2, and V = 140 mph (62.6 m/s).

3. Truck Trailers (Missile)

Three truck trailers parked at the furniture manufacturing company in Xenia, Ohio were moved by tornadic winds to the roof of a

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UPLIFT PRESSURE IN CORNER AREA WHERE $c_p = 5.0$

UPLIFT PRESSURE ON EAVE (END BEAM) $c_p = 2.4$

UPLIFT PRESSURE DUE TO INTERNAL PRESSURE $c_p = 0.8$

DEAD WEIGHT

ROOF BEAM

2' (0.61m)

11.8' (3.60 m)

14.2' (4.33 m)

WELD ANCHORAGE RESISTANCE

OVERTURNING OCCURRED ABOUT THIS POINT (INTERIOR END OF BEAM)
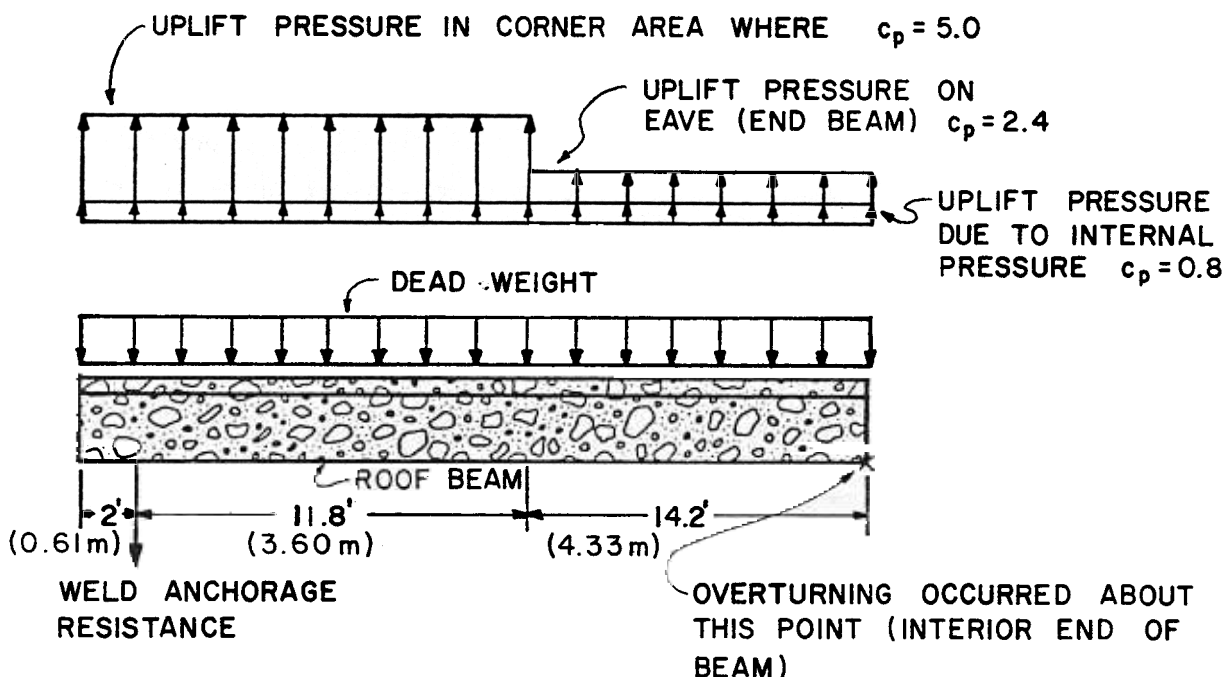
FIGURE 33.   COMPUTATIONS OF WINDSPEEDS USING UPLIFT PRESSURES REQUIRE SEVERAL ASSUMPTIONS. Pressure distributions, weld strengths, and rotation points are parts of the computational procedure.

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one-story bowling alley structure located across the street (Fig. 34). The trailers traveled approximately 150 ft (46 m). The trailer superstructures were made of wood. The truck trailers were not connected to the truck cabs, and they were essentially empty at the time of the tornado incident. Windspeeds required to lift the truck trailers (aerodynamically) can be calculated as follows:

The dimensions of the trailers are 8 ft (2.4 m) wide 12-1/2 ft (3.8 m) high, and 40 ft (12.2 m) long.

(2) The weight of the empty trailer is 12,120 lb (5490 kgf)

(3) Uplift pressure coefficient on flat roof is 0.7, assuming that winds cannot pass underneath the trailers.

(4) Uplift pressure necessary to equalize the weight
$$p = 12,120/(8 \times 40) = 37.9 \text{ psf } (1.8 \text{ kN/m}^2).$$

Using Eqs. (1) and (2), $37.0 = (0.7)(0.00256) V^2$ and $V = 145$ mph (64.9 m/s).

The foregoing calculations do not account for a combination of uplift and overturning of trailers, and thus exposing larger surfaces to the wind. In this event, the calculated windspeed value will be lower than the one previously shown. No attempt is made here to determine flight path of the trailers or the distance through which they traveled.

F. Summary of Tornadic Windspeeds

Establishment of an upper limit for tornadic windspeeds near ground level is important to engineers. The economics of building construction for environmental safety, to mitigate property losses, and to limit personal injuries depend heavily on the value of this upper limit. As discussed in this section, estimation of tornadic windspeeds through engineering analyses can be accomplished with knowledge of wind characteristics, details of the structural system, and wind-building interaction phenomena. Considerable information in these areas is available to engineers, yet the current state of knowledge does not provide total confidence in calculations based upon this knowledge. Hence, it is necessary to judge subjectively the reliability of calculated windspeeds through the use of credence levels.

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FIGURE 34. THE TWO TRUCKS WERE ODD-SHAPED MISSILES. Calculations of
windspeeds required to lift the trucks onto the building
are not considered to be as reliable as other calculations.

The currently accumulated cases of calculated windspeed esti-
mates through engineering analyses (presented in Table II) indicate
that the credibility of estimated windspeeds of 200 mph (89 m/s) or
less is high (credence levels of "good" and "acceptable"). Wind-
speed estimates larger than 200 mph (89 m/s) contain "questionable"
credence level ratings, or are otherwise questionable. These ob-
servations, and subjective judgments by the authors after viewing
thousands of damaged buildings and other structures in 32 wind-
storm events worldwide, lead them to believe that the upper limit
of tornadic windspeeds near the ground is in the range of 250-275
mph (111-123 m/s).

V. NEAR-GROUND TORNADIC WINDFIELDS

A. Importance of Engineering Analysis

The character of near-ground tornadic windfields is an important facet of tornado phenomenology, insofar as the design of structures for tornadoes is concerned. There is very little known about the nature of tornado structure in the portion of the tornado nearest the ground. Inflow patterns near the ground are not well understood. Furthermore, it is not clear that secondary vortices observed in some tornadoes at elevations well above the ground extend into the near-ground regime and become a factor in inducing structural damage.

B. Literature Review*

The oldest written accounts of specific tornadic events appeared in the late seventeenth century. These accounts are studies of the resultant damage patterns rather than descriptions of the tornadoes (Hellman, 1917). Over the centuries, information documenting the damage wrought by tornadoes in many parts of the world has been recorded (Peltier, 1840; Wegener, 1917). These compilations, as well as contemporary studies, remain valuable sources of understanding the nature of windfields in and around tornadoes. Today, as in earlier times, evaluations of damage patterns should be related to conceptual or theoretical models of plausible tornado windfields.

Tornado damage to buildings -- churches, public buildings, etc. -- has traditionally evoked the greatest concern. Dr. Boscovich's account of the tornado of 1749, for example, was largely confined to the damage within Rome, although the tornado had a track extending back from the sea (Desio, 1922). Over the years, such details have allowed computations to be made estimating the strength of the wind, such as was accomplished by Lalanne (1839) for the tornado of Chatenay, France.

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* The authors are indebted to Dr. Richard E. Peterson of the Geosciences Faculty (Atmospheric Sciences), Texas Tech University, for this exhaustive literature review.

The tracks of tornadoes across the countryside have also been noted and offer clues, perhaps more subtle, to tornadic windfields. In uniformly forested regions of Sweden, swaths caused by tornadoes were recognized and attributed to spectres (Grimm, 1883). Within the last century researchers, particularly in Germany, have recorded the pattern of tree falls (for example, Köppen, 1896) as well as the type of tree destruction (Martins, 1850). Larger scale features such as the location of nearby hail swaths and path oscillations were also detailed (Wegener, 1928) in forested as well as farm lands.

The ability of tornado investigators to observe the swaths from above (Letzmann, 1937) has led to the recognition of additional damage signatures. Recently, Fujita has observed apparent spot touchdowns in the form of whorls of downed grain. Earlier, Fujita, Bradbury and Black (1967) catalogued half a dozen characteristic types of ground marks:

1) Captive debris marks, produced by small debris caught on wires;

(2) Scratch marks, caused by sharp-edged objects dragged by the wind;

(3) Bounce marks, observed along the path of a heavy object rolling downwind;

(4 Drift marks, made up of debris oriented in the direction of the final strong wind;

5) Debris marks, consisting of objects removed from an identifiable source; and

(6) Cycloidal marks, appearing as a series of elliptical streaks oriented along the tornado path (first noted by van Tassel, 1955).

Golden and Davies-Jones (1975) have added to this list an apparent debris accumulation strip parallel to the path of the vortex center within the damage swath.

The observed damage can be broadly separated into those features which result from failure of a specific object, as contrasted to those which are due to destruction within a relatively uniform region, such as woods, grain fields or plowed land. Calculations of lower bounds of the windspeed may be best served by the former, whereas an understanding of the wind field as a whole may follow more easily from the latter.

In general, the tornado wind circulation is rather complex. In addition to the translational component, there are vertical, tangential and radial wind components, all of which may change with position (Letzmann, 1923). At some scale there will also be turbulent or irregular motions. Until better understood, the secondary vortices described by Fujita (1975) may have to be considered as turbulence for most purposes, at least in the windfield regime nearest the ground.

Usually, one or more of the possible components has been neglected by those attempting to formulate a model of the tornado. Often the neglect has been forced by the goal of idealization, but sometimes it has been due to the specific conceptual model. A recurring concept, especially in earlier times, envisioned the tornado as a moving plume, with intense inward and upward motions. Trees downed in the direction of tornado translation with the crown converging toward the path center have supported this concept.

In other cases, the evidence for rotational motion has supported vortex models. Classical hydrodynamics offers the potential vortex, which has the whirling motion increasing indefinitely as the origin is approached (Lamb, 1932). Allowing for a finite core in solid rotation yields the Rankine vortex. An upper limit on the wind is established for each specific case in this mode (Letzmann and Wegener, 1930).

Examples of contrary horizontal motions at the base of tornadoes accumulated in the late nineteenth and early twentieth centuries (Kuhlbrodt, 1920) -- largely due to systematic ground surveys in Europe (Letzmann, 1928). The Rankine vortex, which was first applied to hurricane windfields (Sandström, 1909), was used increasingly in tornado studies (Puppo and Longo, 1934). The 1957 Dallas tornado yielded the most comprehensive results (Hoecker, 1960; 1961).

Mathematical studies of possible tornado windfields have moved in several directions (Morton, 1966; Davies-Jones and Kessler, 1974). Largely analytical models (Kuo, 1966; Franz, 1969) as well as numerical simulations (Mal'bakhov and Gutman, 1968; Mal'bakhov, 1972) indicate that the vertical circulation may take one of two configurations: inward and upward along the axis -- one-cell; downward and outward along the axis with upward motions occurring in a sheath about the axis -- two-cell. The outward motions may push to ground level, reminiscent of a suggestion by Rossman (1951).

Time integrations (Gutman, 1969) suggest that the wind flow within a tornado may evolve from a one-cell through a two-cell circulation pattern. In an actual tornado there may be sporadic reversals in the vertical circulation due to environmental variability such as when the tornado encounters the roughness of a terrain covered by buildings.

Attempts to reconcile all deductions of tornado winds within a single circulation pattern are perhaps analogous to the confounding of observations within tropical and extratropical cyclones by meteorologists 100 years ago (Lorenz, 1967). The diversity of possible tornado winds must be incorporated into any analysis of damage patterns. A rapidly translating, but weak, single-cell tornado will yield a markedly different pattern of destruction from that of a slow-moving, vigorous, two-cell vortex. Furthermore, a sequence of characteristic damage patterns along the tornado path may be indicative of evolutionary changes in the circulation taking place during the life cycle of the tornado. Such evidence eventually should support theoretical models of tornado genesis and decay.

C. Evaluations of Existing Engineering Documentations

During the past six years engineers have begun to make increasingly closer examinations of tornado-induced damage. Investigators from Texas Tech University have visited the scenes of 32 extreme windstorm events, and investigators representing civil defense interests, the architecture and engineering professions, the nuclear industry, and academia have increased the rate of conduct of technical post-storm investigations as well. The results of this activity constitute a relatively new body of literature on wind-induced damage, as well as extensive unpublished data of an engineering nature on damage and debris caused by tornadoes. It is these data, both published and unpublished, which form the basis of modern understandings of near-ground tornadic windfields.

Several published storm damage documentations have been reviewed for windspeed and windfield data which have heretofore gone unused in terms of defining tornadic windfields. The Lubbock Storm (Mehta et al., 1971) and the Tornadoes of April 3-4, 1974 (Mehta et al., 1975; Almuti, 1974; Mehta et al., 1976) are major events for which published

data are available. Documentations of other windstorm events are useful as well (McDonald, 1971; Sanders et al., 1975). Unpublished data on each of the 32 events mentioned above are available at Texas Tech University (Table III). Additional unpublished data files of an engineering nature are known to exist at Ball State University (Indiana tornadoes of April 3-4, 1974), at the University of Detroit (Michigan, Indiana, and Ohio tornadoes of April 3-4, 1974), at Iowa State University (the Omaha Tornado of May 6, 1975 and selected Iowa tornadoes), with Bechtel Power Corporation, with the Nuclear Regulatory Commission, with the National Bureau of Standards and with the Defense Civil Preparedness Agency. All of these documentations and data files represent potential sources of information for researchers who address the general topic of near-ground tornadic windfields.

D.   Engineering Evaluations

The approach taken in reviewing and synthesizing engineering data from tornado events follows two paths. Windspeeds in specific tornado events are sought as indicators of maxima which may occur in any tornado event. Secondly, damage and debris patterns are examined for clues regarding the character of near-ground windfields. Central to these latter investigations are attempts to determine if the seemingly disorganized pattern of tornado-induced damage results (1) from meteorologically induced discontinuities in the windfields (e.g. local perturbations in the vortex or secondary vortices in contact with the ground), (2) from mechanically induced turbulence resulting from wind-structure interactions, or (3) from differences in building construction, geometry, and orientation.

1.   Extreme Winds and Their Location in the Windfield

Results of investigations into windspeed maxima are presented and discussed in Section IV (Tornadic Windspeeds). As noted therein the windspeed maxima data have profound implications for engineering undertakings. Where the geometries of tornadic windfields are concerned, directions of these maxima within the tornadic windfield are important. It is of significance, for example, to note whether the directions of largest windspeeds established in a tornado damage path are consistent with the general vortex circulation (i.e. the "parent" vortex) or whether these directions are randomly oriented.

TABLE III

WINDSTORM INCIDENTS DOCUMENTED BY
TEXAS TECH UNIVERSITY PERSONNEL

Investigation Number	Location	Type of Windstorm	Date
1	Lubbock, Texas	Tornado	May 11, 1970
2	Corpus Christi, Texas	Hurricane Celia	August 3, 1970
3	Hereford, Texas	Tornado	April 19, 1971
4	Amarillo, Texas	Windstorm	June 22, 1972
5	Hubbard, Texas	Tornado	March 10, 1973
6	Burnet, Texas	Tornado	March 10, 1973
7	Sweetwater, Texas	Windstorm	March 23, 1973
8	Plainview, Texas	Tornado	April 15, 1973
9	White Deer, Texas	Tornado	May 1, 1973
10	Joplin, Missouri	Windstorm	May 11, 1973
11	Big Spring, Texas	Windstorm	September 4, 1973
12	Louisville, Kentucky	Tornado	April 3, 1974
13	Brandenburg, Kentucky	Tornado	April 3, 1974
14	Xenia, Ohio	Tornado	April 3, 1974
15	Guin-Huntsville, Alabama	Tornado	April 3-4, 1974
16	Hamilton-Moulton, Alabama	Tornado	April 3-4, 1974
17	Jasper-Cullman, Alabama	Tornado	April 3-4, 1974
18	Monticello, Indiana	Tornado	April 3, 1974
19	Drumright, Oklahoma	Tornado	June 8, 1974
20	Tulsa, Oklahoma	Tornado	June 8, 1974
21	Lafayette, Louisiana	Hurricane Carmen	September 1974
22	Darwin, Australia	Cyclone Tracy	December 25, 1974
23	McComb, Mississippi	Tornado	January 10, 1975
24	Atlanta, Georgia	Tornado	March 24, 1975
25	Omaha, Nebraska	Tornado	May 6, 1975
26	Tulsa, Oklahoma	Tornado	December 5, 1975
27	Washita, Oklahoma	Tornado	April 17, 1976
28	Crowell, Texas	Tornado	April 17, 1976
29	Graham, Texas	Windstorm	May 25, 1976
30	Birmingham, Alabama	Tornado	April 14, 1977
31	Monahans, Texas	Tornado	April 19, 1977
32	Levelland, Texas	Tornado	May 20, 1977

If a clear pattern exists, then it may be concluded that the largest windspeeds are associated with parent circulation. On the other hand, if maximum windspeed directions are randomly oriented, large windspeeds may be identified with small-scale wind motions, such as may be inferred from concepts of secondary vortices.

Perhaps the best documented analysis of large windspeeds within a tornado path was accomplished by Mehta et al. (1971) in the study of the Lubbock Tornado of May 11, 1970. In this exhaustive evaluation, ninety-three building failures and missile events which represented points judged to have experienced relatively large windspeeds were evaluated. The specific points were selected from areas which received the most extensive damage. Directions of maximum windspeeds which occurred at these points were established. Figure 35 illustrates the results of this evaluation. Directions of large windspeeds occurring at the selected points indicate that the largest windspeeds within the windfield were following the large cyclonic circulation attendant to the Lubbock Tornado. Essentially all of the arrows fall in directions tangent to large diameter circles centered at points along the tornado path.

Similar conclusions can be drawn from investigations of other major tornado events which affected inhabited areas and engineered buildings. Although not receiving the exhaustive treatment as was the case in the Lubbock Tornado study, evaluations of the Xenia (Ohio) Tornado and the Monticello (Indiana) Tornado, of April 3-4, 1974, and the Omaha Tornado of May 6, 1975 indicate that the largest windspeeds occurred in directions which coincide with the parent vortex circulation. Investigators working on the ground walked the damage paths in each of these events and recorded directions of winds which caused the most severe damage to engineered structures. Several of these records are noted for the Xenia Tornado in Figure 36. Of particular importance are extreme wind directions at several engineered school structures. Extreme wind directions are noted in Figure 37 for the Monticello Tornado and in Figure 38 for the Omaha Tornado. In situations where the extreme wind direction could be determined, the direction coincides with a direction which would be expected from a parent vortex with cyclonic circulation traveling along a line which is centered on the damage path.
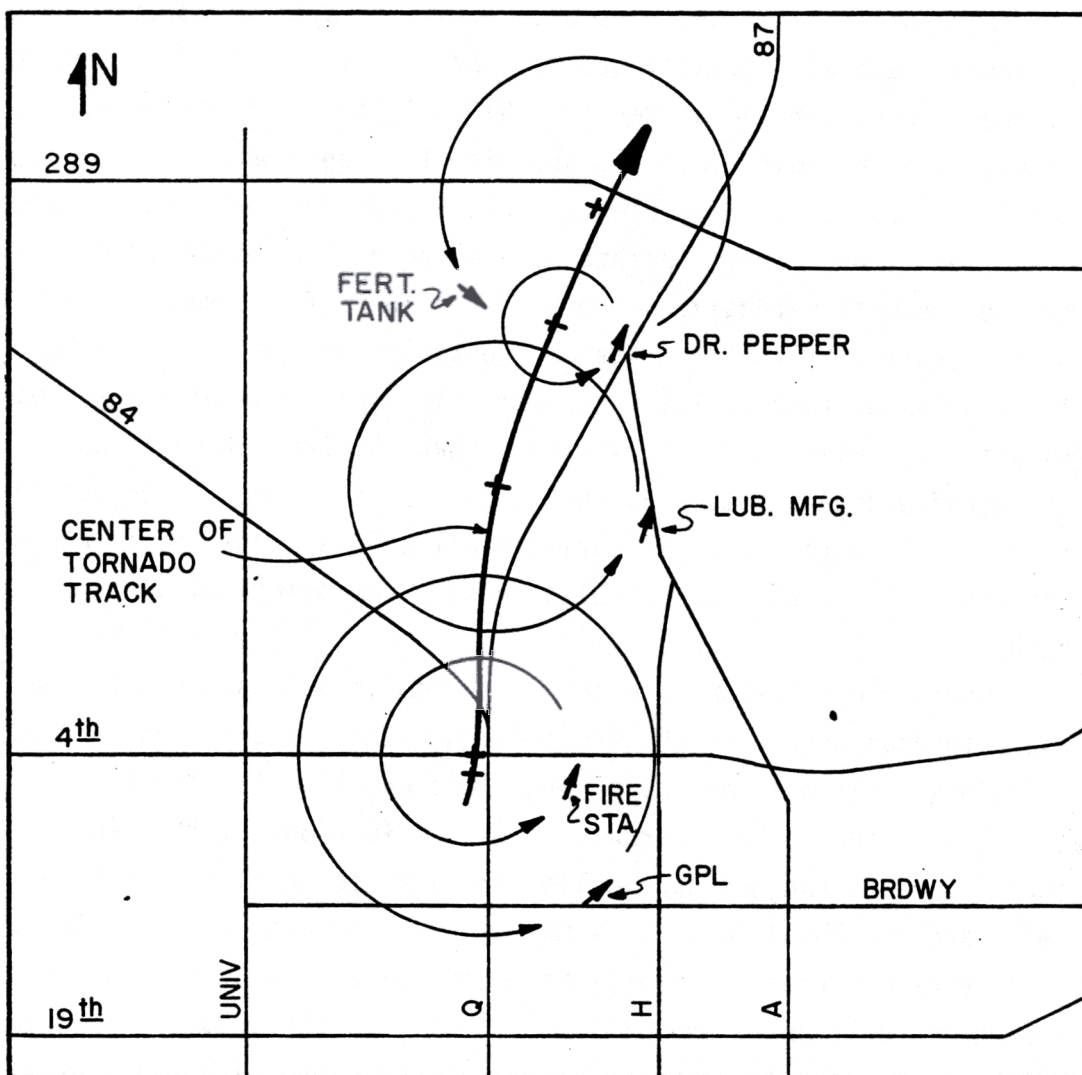
FIGURE 35   DIRECTIONS OF EXTREME WINDS SEEM TO BE ASSOCIATED WITH
PARENT VORTEX ROTATIONS. Points at which extreme winds
were verified in the Lubbock Tornado indicate that ex-
treme wind directions coincide with circles centered
on tornado track center line.
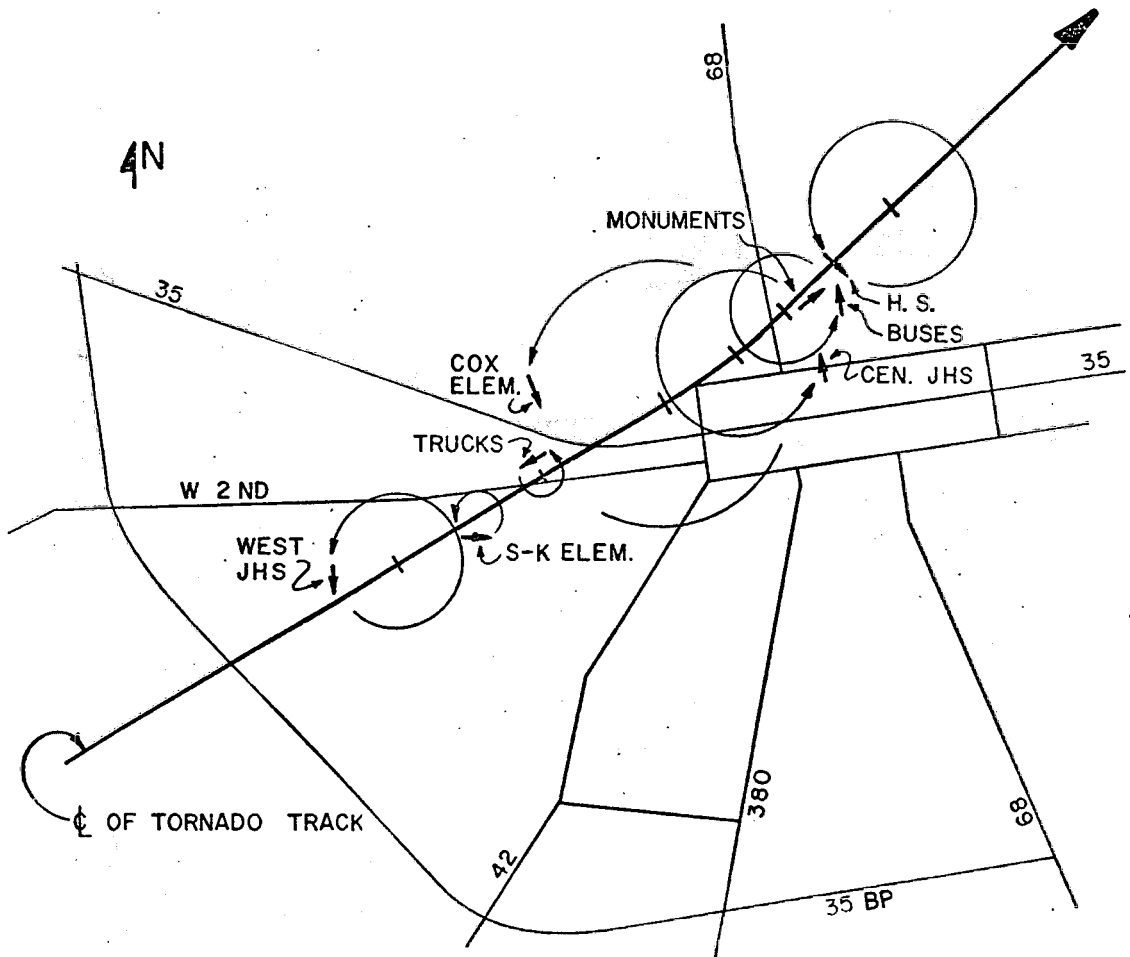
FIGURE 36. EXTREME WIND LOCATIONS REFLECT WIND DIRECTIONS WHICH COINCIDE
WITH PARENT VORTEX ROTATIONS. Points of analysis in Xenia,
Ohio (Mehta et al., 1976) fit the windfield pattern suggested
by the parent vortex.
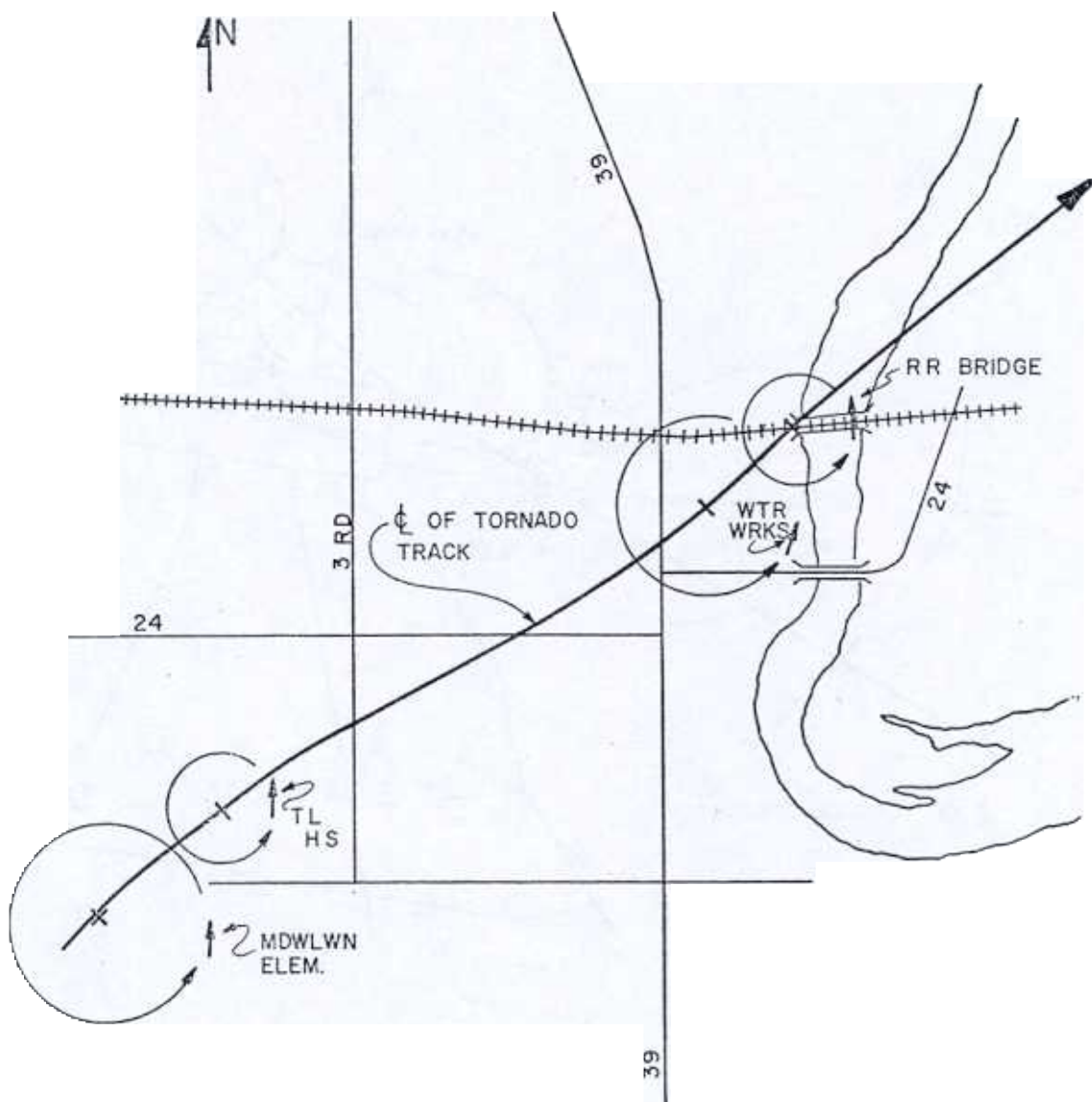
FIGURE 37. EXTREME WIND DIRECTIONS IN MONTICELLO, INDIANA FIT CLASSIC
PARENT VORTEX PATTERN. April 3, 1974 tornado crossed en-
gineered school buildings and a railroad bridge (Mehta et
al., 1975).
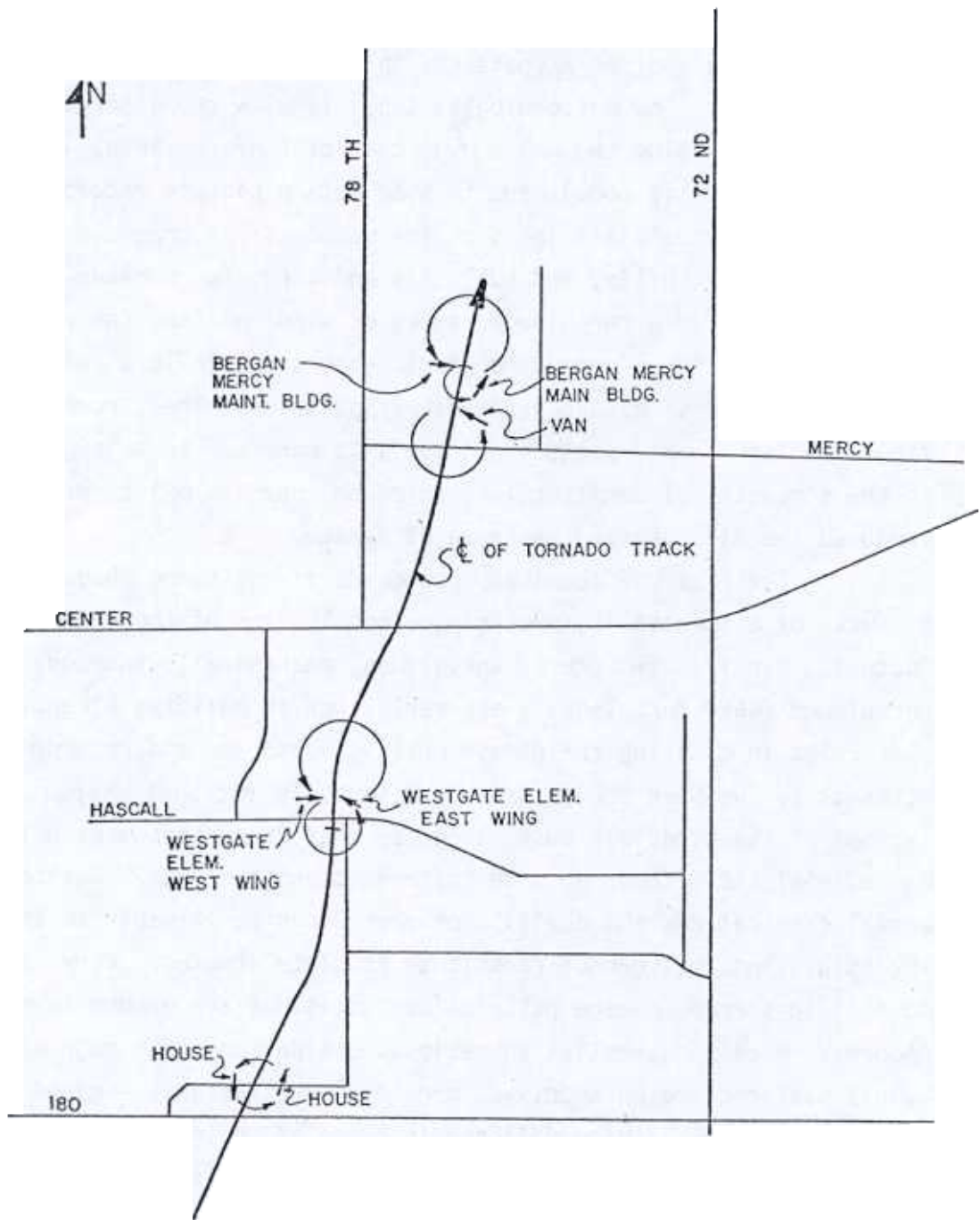
FIGURE 38. EXTREME WIND DIRECTIONS IN OMAHA, NEBRASKA TORNADO SUGGEST CLASSIC VORTEX WINDFIELD. The May 6, 1975 tornado affected several fully engineered structures.

2. Tornado Damage Patterns

Investigators who examine tornado damage tend to interpret what they see in the debris patterns in terms of their own backgrounds and perceptions. The meteorologist tends to view the disorganized damage pattern as reflecting the non-uniform character of the tornadic windfield which he sees in his models and in some motion picture records. The fluid dynamics specialist looks at the roughness of ground surfaces containing trees, hills, and buildings and tends to conclude that mechanically-induced turbulence caused by wind-building interactions in the boundary layer produce dramatic excursions in local windspeeds which contribute to disorganized debris patterns. The structural engineer views the same debris pattern and tends to conclude that large variations in the strengths of construction, which he knows to exist, must have produced the disorganized patterns of damage.

The cause of seemingly random debris patterns observed in the wake of a tornado is, probably, a combination of the above factors. Surely, atmospheric turbulence, mechanically-induced turbulence (wake turbulence), and variations in building strength play roles in creating the damage which is observed and recorded. Attempts to decipher the patterns and to build rational characterizations of the windfield must recognize that these phenomena exist. Hence, analysis methods must be systematic and thorough. Cursory aerial examinations and aerial photography can be valuable to such investigations, but cannot constitute complete studies. Very important to tornado damage pattern investigations are ground-level records. Perhaps essential to rational evaluations of damage and debris patterns are perspectives provided by structural engineers who can evaluate building failures in terms of their original wind resistance, failure mode, and overall character. It is in this latter area where meaningful contributions can be advanced by the engineer.

Mehta et al. (1971) in reporting their work following the Lubbock Tornado concluded that "the disorganized pattern of structural damage ... can be more satisfactorily explained by noting variations in the abilities of structures to resist wind forces, than by relying on complex meteorological theories which assume dramatically

different wind velocities within short distances." Investigations of thirty-one subsequent windstorms by the same investigators and investigations of windstorm events by others (Sanders et al., 1975; Walker, 1972, 1975) offer conclusions which tend to support this observation.

Discussions of damage to housing advanced in the next section of the report (Section VI) illustrate the meaning of the above assertion. Factors such as roof geometry, orientation of garages and porches, anchorages (roof-to-wall and wall-to-foundation), and construction quality can make one house perform very poorly relative to adjacent units. In the case of fully engineered, marginally engineered, and pre-engineered buildings (see Section III.B for definitions), similar effects can be noted. Failures of overhead doors or large windows which happen to be in windward walls provide the most often encountered situation in which a building is destroyed while adjacent buildings remain intact. Examples of this common occurrence are illustrated in Figure 39. Also common are building failures caused by poor construction quality located adjacent to buildings of more substantial quality (Fig. 40). While local perturbations in the windfield may be present and could contribute to differences in levels of damage, it appears that wind resistance capacity inherent to the structure plays a major role.

The occurrence of local damage to a structure is sometimes associated with a local "gust of wind" or the passage of a "secondary vortex." It is pointed out in the discussion of building failure modes (Section III) that concentrations of outward-acting pressures occur on structures subjected to "straight"* winds at corners of walls and corners of roofs. Hence, the occurrence of damage to a building corner (Fig. 41) should not be interpreted as being caused by a local wind perturbation, but, rather, the damage should be treated as a reflection of dramatically different pressures induced at building corners by air flowing over sharp discontinuities.

Finally, reference is sometimes made in the popular literature to a phenomenon termed "cyclonic twist." Houses have been

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*Although tornadic windfields are cyclonic and, hence, "curved," the winds experienced by a given building are essentially straight, especially if the building is small relative to the diameter of the tornado.

FIGURE 39. OVERHEAD DOORS OR OPENINGS IN WINDWARD WALLS OFTEN PROVIDE FAILURE INITIATION POINTS. The metal building (top) and Central Fire Station (below) in Lubbock sustained damage because of windward wall failures involving doors.

FIGURE 40.   WEAK STRUCTURES ADJACENT TO STRONG STRUCTURES MAY MISLEAD DAMAGE
INVESTIGATORS WITH REGARD TO WINDFIELD GEOMETRY. The inadequate
connection detail (top) made the warehouse susceptible to wind
damage at relatively low windspeeds (bottom).

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FIGURE 41. OUTWARD ACTING PRESSURE CONCENTRATIONS AT BUILDING CORNERS
CAUSE LOCAL DAMAGE. The damage investigator should not
conclude that a tornado passed over the corner of this
warehouse.

observed to "twist" under the influence of windloads. Analysis of these situations as they occur in the field suggests that the rotation is more of a function of non-uniform wind resistance, as opposed to non-uniform windloads. Most houses which are removed from their foundations are asymmetrical -- both in geometry and in house-to-foundation connection strength. Hence, a uniformly applied lateral load (uniform wind pressure on windward wall) will produce asymmetrical reactions in house-to-foundation connections. This asymmetrical nature of the resistance to sliding will invariably produce rotation of the unit as it slides off of its foundation (Fig. 42). In fact, it would be an exception for a house to offer uniform resistance to sliding, principally because of concentrations of resistance to sliding presented by plumbing connections. The Great Plains Life Building was "twisted" by the Lubbock Tornado (McDonald, 1970). Here, differences in structural stiffness, rather than variations in wind pressure, were the cause of asymmetrical response (Fig. 43).
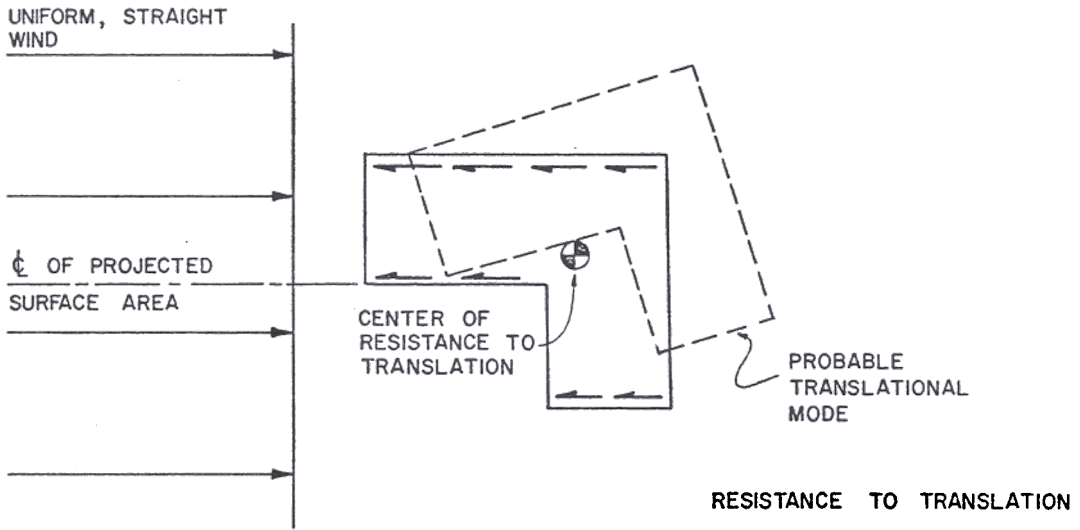
(a) ASYMMETRICAL BUILDING
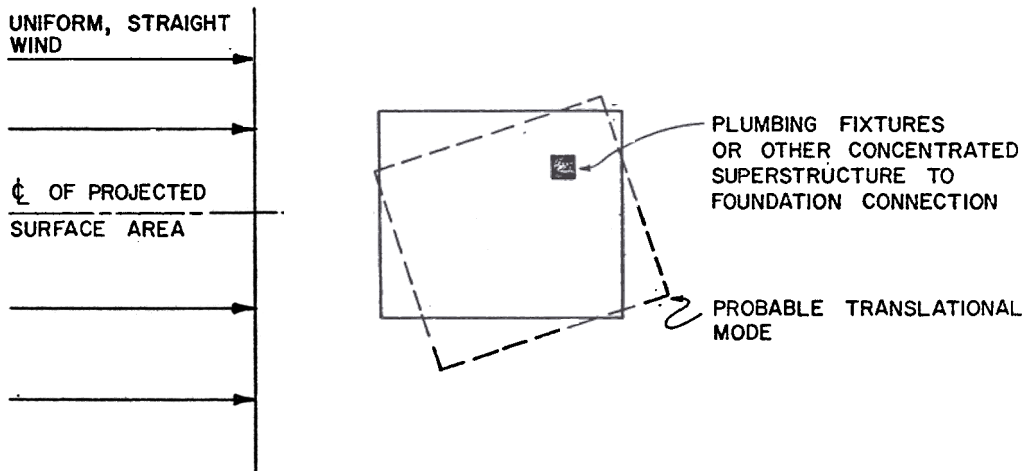
(b) SYMMETRICAL BUILDING

FIGURE 42. TRANSLATION AND ROTATION OF BUILDINGS INFLUENCED BY UNIFORM WIND LOADS ARE GOVERNED BY SUPERSTRUCTURE-TO-FOUNDATION CONNECTION DETAILS. Only in rare instances will translation not be accompanied by rotation.

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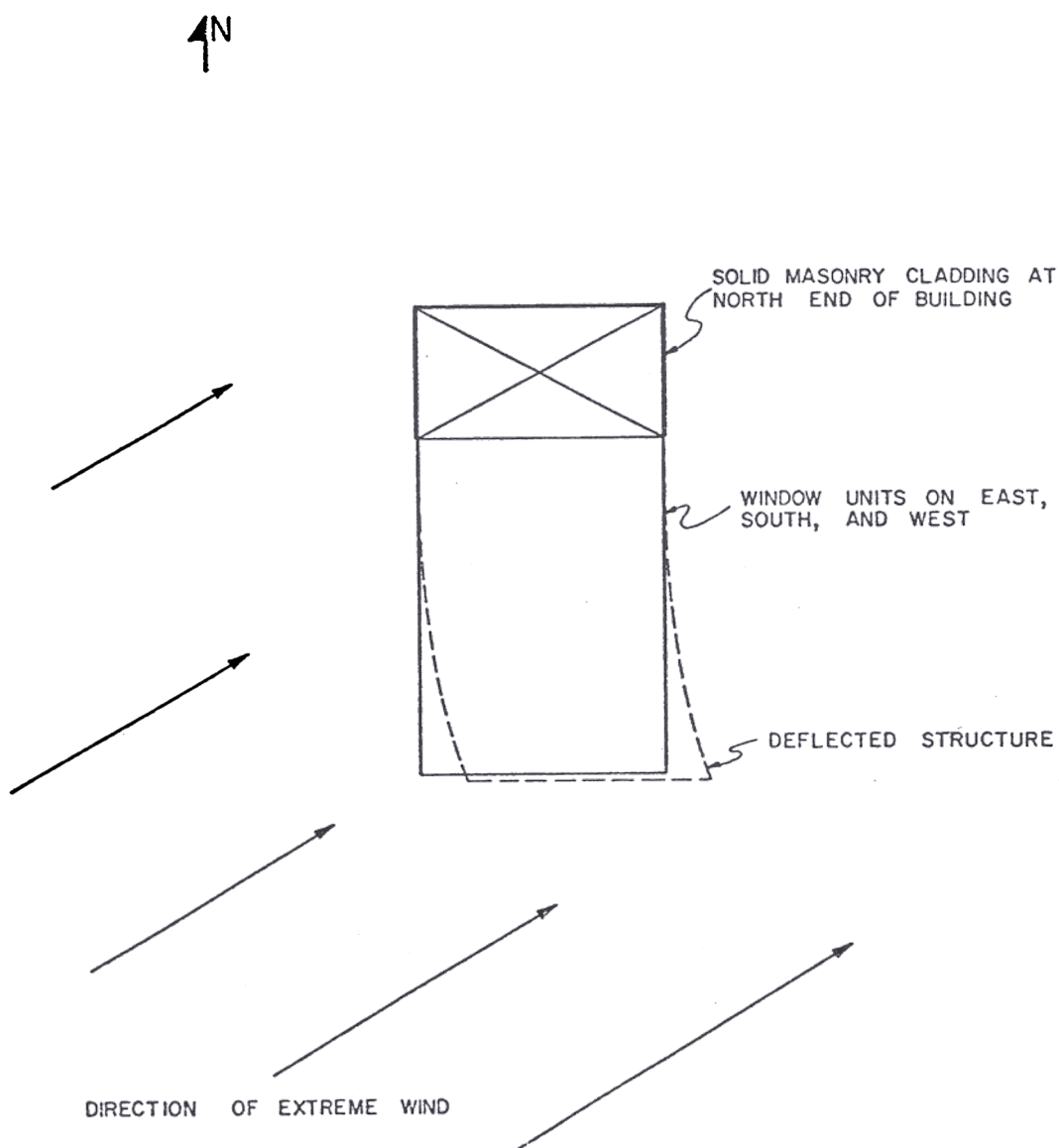
FIGURE 43. GREAT PLAINS LIFE BUILDING WAS "TWISTED" DURING PASSAGE OF THE LUBBOCK TORNADO. McDonald (1970) concluded that the permanent deformation in the structural frame was the result of differences in stiffness and strength presented by the solidly clad, north end of the building.

VI. PERFORMANCE OF HOUSING

A. Information from Housing Damage

Single family residences are, by far, the most common type of structure that is influenced by tornadic winds. This fact suggests that the data base which involves housing damage from tornadoes should be a valuable asset to the conduct of engineering and scientific investigations which relate to tornado-structure interaction and to the definition of tornadic windfields. While housing damage can tell the investigator much about the character of tornadic winds, extreme care must be exercised in interpreting these data. Several types of information which can be extracted from housing damage are discussed below: wind direction, tornado path width, and windspeed.

Generally, housing damage is a good indicator of the direction of maximum winds which occurred at the house location. Examination of the manner in which a given house failed almost invariably provides a clear indication of a direction which can be identified with maximum winds. In all cases, except a few situations which involve very large houses, investigators on the ground have had no trouble in establishing the direction of maximum winds through analysis of housing failure modes, using the concepts of structural failure advanced in Section III. Examples of housing damage taken from the Plainview Tornado illustrate this point (Ref. Fig. 44). It is also apparent to investigators that houses which are damaged in tornadoes are affected by extreme winds which act on the structure from a single predominant direction. There is little evidence which suggests that extreme winds act on houses simultaneously from different directions (i.e. from a very small vortex). Finally, it must be emphasized that it is the analysis of structural failure, not analysis of the debris pattern, which establishes the direction of maximum winds at the location of the house. Debris patterns surrounding a damaged house can be very misleading in windfield geometry assessments, particularly if the debris pattern is viewed only from the air. Oftentimes the source or character of the debris is

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FIGURE 44. THESE HOUSES IN PLAINVIEW, TEXAS FAILED FROM FRONT TO REAR,
BEGINNING IN THE GARAGE AREAS. This failure mode is clear
evidence of the direction of extreme winds.

misinterpreted when viewed from a distance. The direction of debris movement can be incorrectly assessed because of erroneous assumptions regarding debris origin or because the debris was moved prior to aerial observation. Debris can also be moved by winds which are less than the maximum which occurred, making determination of directions of maximum windspeeds difficult to assess from debris patterns. Figure 45 contains aerial and ground photographs of a housing area in Xenia, Ohio which was affected by the Xenia Tornado of April 3, 1974. Note that the streak of debris emanating from the corner of the elementary school may appear to be the result of a "streak" of wind in the aerial photograph. In the ground level view, the result of the stopping by the school of some of the debris can be seen. The "streak" of debris was not caused by a perturbation in the windfield but, rather, by modification of the debris pattern by the school.

Housing damage data can also be used to determine the width of the tornado path. A windspeed of 75 mph (34 m/s) is considered to be the value at which damage begins to occur to housing. Damage caused by 75 mph (34 m/s) winds is usually reflected in minor roof damage (shingles removed), some glass breakage, damage to fences, carports and awnings, some tree damage (limb breakage) and damage to commercial signs (large billboards). Damage caused by 75 mph (34 m/s) winds may be difficult to observe from aerial photographs. Ground surveys may be needed to supplement the aerial survey if an accurate determination of tornado path width is required. Accurate path width determinations are useful in studies of windfield geometry, in photogrammetric work where the location of the tornado with respect to the camera is important, and in developing tornado risk models which consider aerial coverage of tornadic winds.

Where windspeeds in tornadoes are concerned, housing can provide some general estimates of windspeeds in lower windspeed ranges, and some coarse distinctions between moderate and severe winds can be obtained for higher windspeed ranges. Table IV provides descriptions of residential damage in terms of increasing windspeed, if the housing is of a general quality which is typical of cities with

FIGURE 45.

CARE MUST BE EXERCISED IN EVALUATING DEBRIS PATTERNS FROM AERIAL OBSERVATIONS. The streak of debris (top photograph) was caused by modifications of the debris pattern by Arrowood School (bottom photograph) in Xenia, Ohio.

TABLE IV

TORNADO DAMAGE TO RESIDENCES

Windspeed Range	Damage Description	Windspeed Range (mph)	Equivalent F-scale
	TV antennae bent; a few roof shingles blown off; light weight awnings and canopies damaged.	40-75 (18-34 m/s)	F0
	Windows broken by flying debris; large sections of shingles removed from roof corners and eaves; residential chimneys collapsed.	75-110 (34-49 m/s)	F1
	Sections of roofs and porches damaged, especially if inadequately anchored; large sections of gabled roofs may be torn off on leeward side; carport roofs lifted; extensive damage to garage roofs, if door is on windward side.	110-130 (49-58 m/s)	F2
	Entire roofs removed and carried away by the wind, leaving first floor walls standing; roof removed from two story houses, some second story exterior walls collapsed. Roofs undamaged only if extraordinary anchorage precautions have been taken, such as the use of hurricane clips.	130-160 (58-72 m/s)	F2-F3
	Two-story residences almost completely destroyed; exterior walls on single story dwellings collapsed with only well supported interior walls standing.	160-200 (72-89 m/s)	F3
	Little remains intact; debris scattered down path of the tornado.	>200 (>89 m/s)	F4

building codes and a strong codes enforcement program. Table IV
was developed by four investigators at Texas Tech University who
have observed windstorm damage to houses for six years. Photographs
which illustrate each of the six categories of damage are shown in
Figure 46. Comparisons of the residential damage description ad-
vanced here for code-enforced housing with the Fujita-scale descrip-
tions of damage (Fujita, 1971) are shown in Figure 47. There is rela-
tively good agreement between the two damage vs. windspeed relation-
ships at the lower windspeeds, but above about 125 mph (56 m/s) the
Fujita scale associates much higher windspeed with damage that is
similar in description to the descriptions advanced in Table IV.
A principal reason for this difference seems to be methodology. An
individual house should not be examined with the objective of making
a windspeed estimate, nor should a distinction be made between wind-
speeds which occurred at adjacent house locations because one of the
two houses had a different degree of damage. The many variables which
govern the behavior of a house in a windstorm (discussed below) make
degrees of individual housing damage unreliable indicators of tornadic
windspeeds. Only where some standard of construction quality can be
established, e.g. in an incorporated city with a building code and an
active code enforcement program, can windspeed estimates from housing
damage be attempted. (Rural housing is a very poor indicator of tor-
nadic windspeeds.) It is necessary to examine several houses in a
group before making windspeed assessments such as those advanced in
the first three windspeed ranges in Table IV. Development of coarse
distinctions between moderate windspeeds (125-150 mph) (56-67 m/s)
and severe winds (150-200 mph)(67-89 m/s) also involves more than
the viewing of individual houses, or assessments of the appearance of
damage in aerial photographs. Figure 48 shows aerial views taken in
Xenia, Ohio following the Xenia Tornado of April 3, 1974. The tornado
path, defined by limits of damage caused by 75 mph (34 m/s) winds or
greater, covers the entire photograph. In the section just above West
Junior High School in Figure 48, some houses are totally destroyed,
leaving nothing but debris. Other houses have their roofs removed but
their walls are still standing. Roofs and walls are intact on a few
other houses, although there is considerable damage to the structure.

FIGURE 46. ILLUSTRATIONS OF RESIDENTIAL DAMAGE IN EACH OF THE SIX DAMAGE
CATEGORIES DESCRIBED IN TABLE IV. The indicated windspeed
occurred only if (1) the damage is typical of several units
in an area and (2) the housing was constructed under pro-
visions of an enforced building code.

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WINDSPEED - MPH (M/S)
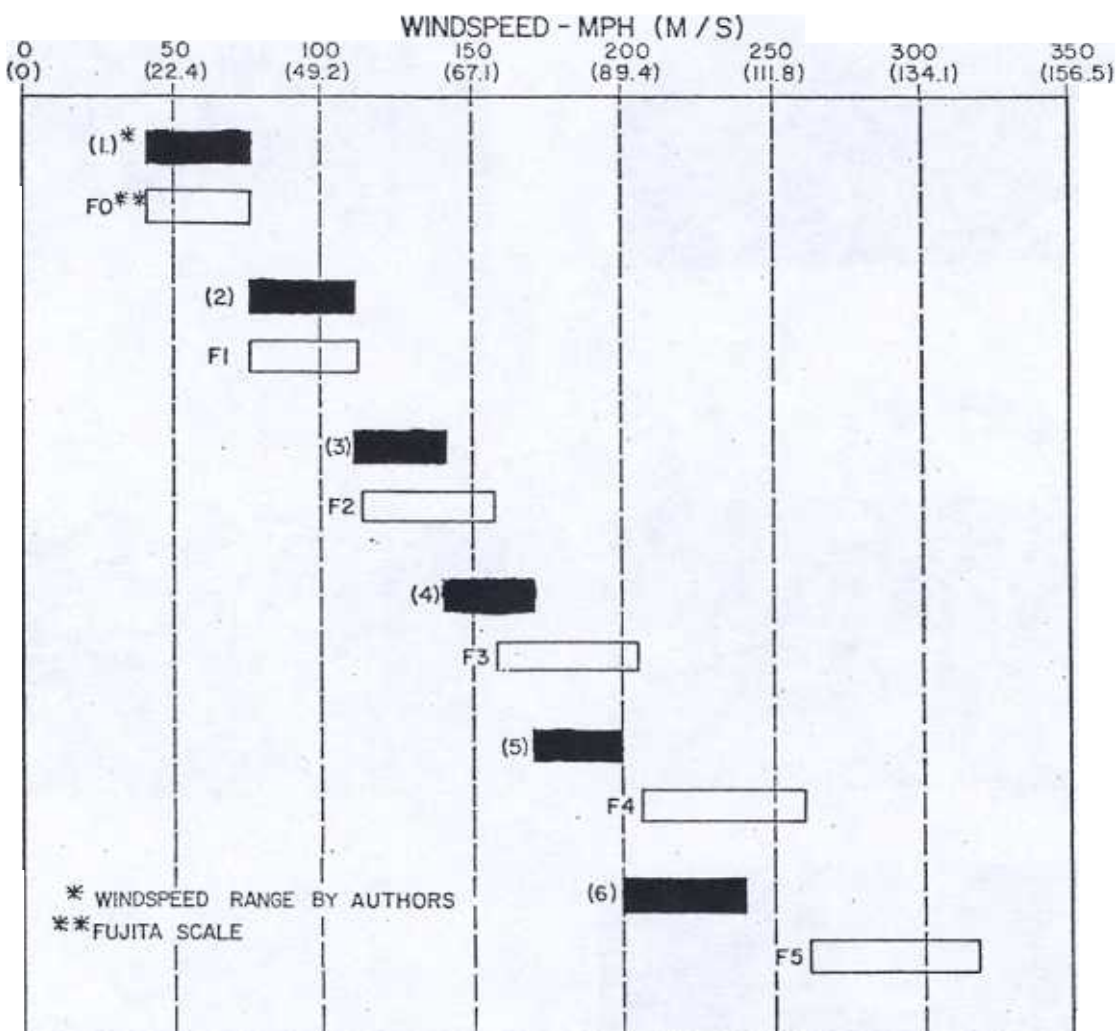
FIGURE 47.   COMPARISONS OF FUJITA SCALE AND DAMAGE VS. WINDSPEED
RELATIONSHIPS ADVANCED IN TABLE IV. Comparisons are
good in lower windspeed ranges, but diverge in ex-
treme wind ranges.

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An overlay of the photo in Figure 48 is shown in Figure 49. Here each house is indicated by a (V), a (X), or a (Z), depending upon the extent of damage. A (V) means that the roof on the house is still intact, an (X) means that the roof is removed but some walls are still standing, and a (Z) indicates that nothing is left but debris. Note that even in the hardest hit areas there are a few houses that were not totally destroyed. This variation in degree of damage is easier to explain as being caused by variation in construction, orientation, or other factors (discussed below) rather than by dramatic variations in tornadic wind-speeds. There is a fairly clear distinction between those houses with roof intact and those with more extensive damage. This path is out-lined in Figure 49. These lines provide the coarse distinction be-tween moderate and extreme winds.

In summary, these discussions and those presented below indicate that damage to residences can be good indicators of wind direction and tornado path width, but is not considered to be reliable in esti-mating tornadic windspeeds. Mehta (1976) in defining credence levels for windspeed calculations places residences in the questionable (least reliable) category. This does not mean, however, that residential damage cannot give some indication of relative windspeeds. A number of residences must be considered, or an entire area along the path length must be taken collectively, if a reasonable estimate is to be made.

B. Behavior of Housing in Windstorms

It is easy, and tempting, to generalize about tornadic windfields when much damaged housing data are available. Such generalizations can be erroneous if certain understandings of the behavior of housing in windstorms are not considered. Discussed below are several factors which influence the behavior of housing in windstorms, including tor-nadoes. Critical to housing behavior are construction practice, house orientation with respect to the wind, house geometry, shielding by adjacent structures or trees, and terrain.

1 Construction Practices

Construction practice is the most significant factor that in-fluences the resistance of a house to tornadic winds. These practices

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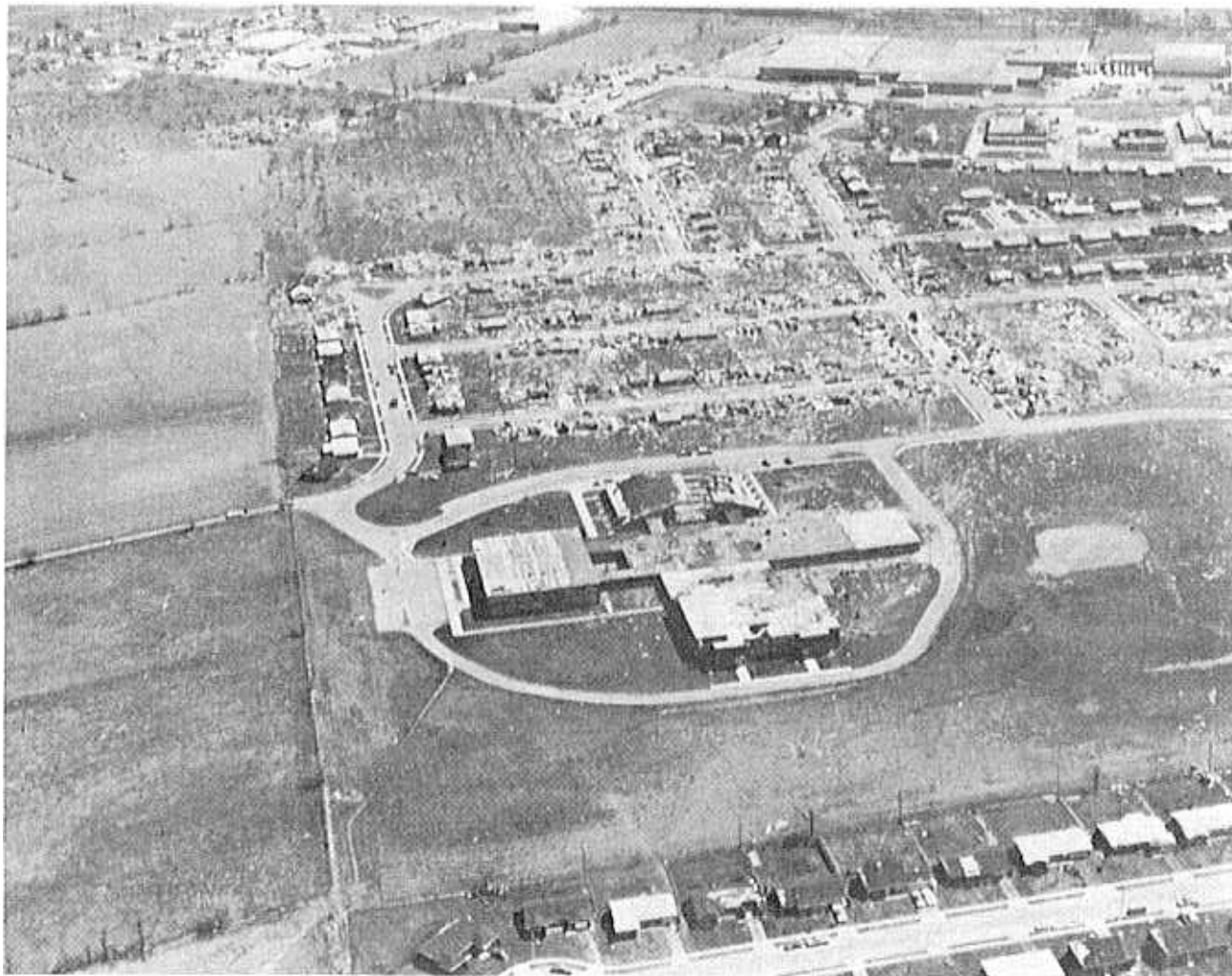
FIGURE 48. HOUSING DAMAGE IN XENIA, OHIO FOLLOWING THE TORNADO OF APRIL 3, 1974.
Even where the destruction is the most severe, some units are
partially intact.
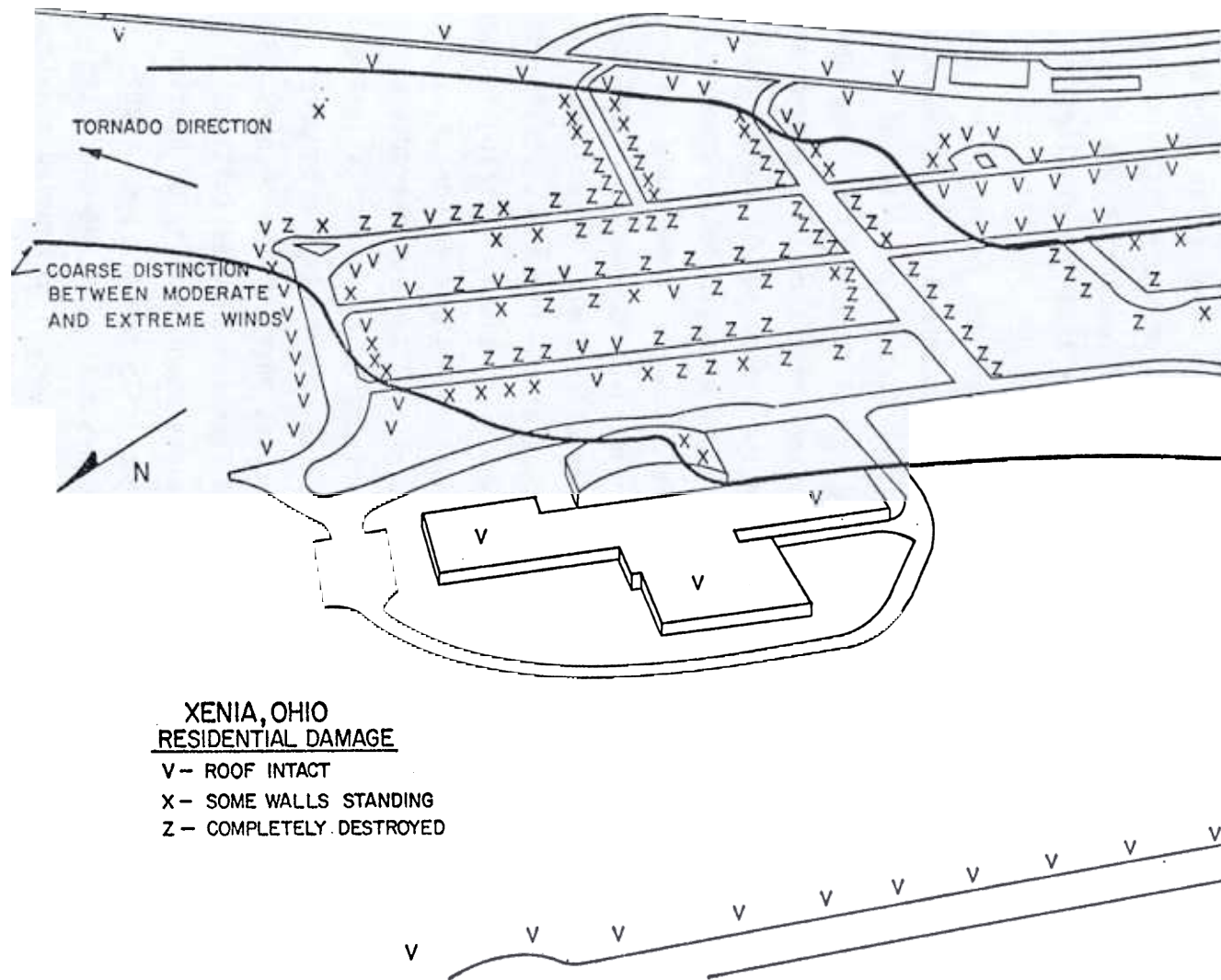
FIGURE 49. OVERLAY OF FIGURE 48. Variations in degree of damage to housing are emphasized by examining damage to groups of houses.

vary, sometimes drastically, from one region of the country to another, and between rural and city settings. Examinations of housing throughout the country, including the Southeast, South, and Southwest, and Midwest, have led engineering-oriented investigators to conclude that (1) unzoned rural construction is markedly inferior to construction within cities which have active building code enforcement programs, and (2) traditional methods of housing construction evolve differently in large cities. These factors often lead to large variations in housing behavior during windstorms. Each of these conclusions are illustrated below.

Rural housing is characterized by light framing, poor foundation anchorage, and minimum attention to connections. While exceptions occur in construction quality, the fact that no city or zoning authority enforces strict codes leads rural construction to be, generally, inferior to housing construction where such code enforcement is present. The most commonly occurring phenomenon in rural areas is a house or an "out building" which has been completely removed from its foundation (Fig. 50). While awesome in appearance, especially from the air, ground level investigations usually reveal weaknesses in construction practice. Most often there is complete lack of anchorage between the superstructure of the house and its foundation (Fig. 51). Common are houses which are simply "sitting" on concrete block piers or perimeter foundations with no anchorage systems which would resist sliding or overturning of the superstructure.

As investigators have traveled from city to city in the wake of tornado events, they have had an opportunity to compare housing construction practices in various parts of the country. A subjective judgment that has evolved from these investigations is that regionally-oriented generalizations about quality of housing construction can be made, but that each city has its own "traditional" way of doing things. It appears that over the years the builders in each city have developed approaches to housing construction which are deeply engrained in the trades. Referred to as the "traditional" approach to housing construction (Walker, 1976) these methods are not likely to change unless a major event,

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FIGURE 50.   RURAL HOUSING IS CHARACTERIZED BY POOR SUPERSTRUCTURE-
TO-FOUNDATION CONNECTIONS. This house in Drumright,
Oklahoma was moved intact from its foundation (fore-
ground) because there are no anchoring devices.

FIGURE 51.   HOUSES WITH NO ANCHORAGES HAVE LITTLE RESISTANCE TO LATERAL FORCES.
            Note the smooth, anchor-free surface on the perimeter foundation
            of this rural house near Tulsa, Oklahoma.

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such as a windstorm or an earthquake, compels corrective action. Since such major events are rare, certain practices which make housing vulnerable to wind go uncorrected and reveal themselves in dramatic fashion when a windstorm occurs.

Two examples are offered to support the above judgments regarding traditional methods of construction in cities. It became apparent in studies of the Plainview Tornado of April 15, 1973 that contractors had established a roof framing tradition that consisted of forming "gables" with rafters extending from the eave to the ridge line. Even in larger houses with widths of 50 feet or more, only rafters were used, leaving a completely open space in the attic. (Recommended practice would employ "trusses" or additional framing in the attic space.) The result of this practice is a roofing system with little resistance to lateral loads. Failure modes commonly involve complete removal of the leeward half of the roof (Fig. 52). The other example of traditional construction methods is taken from Omaha, Nebraska. The tradition there is the building of house superstructures on perimeter foundations. The perimeter foundations are partially buried concrete block walls which usually surround a basement (Fig. 53). Apparently, a technique of construction used for many years in Omaha simply placed the superstructure on the perimeter foundation with little or no anchorage between the two. Results of this practice are illustrated in Figures 54 and 55 where entire superstructure units have been moved, intact, from their foundation. Analysis has shown that translation of the house can occur at relatively low windspeeds, perhaps as low as 100 mph (44.7 m/s).

2. House Orientation

Forces which act upon walls and roofs of houses are dependent upon such factors as the amount of openings in windward walls and the orientation of large surfaces with respect to the direction of approaching wind (Ref. Section III for a discussion of wind-induced forces on buildings). It has been found through damage investigations that houses oriented such that an attached garage faces the approaching wind are more susceptible to failure than houses without attached garages, or with garages which do not face approaching winds.

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FIGURE 52. TRADITIONAL METHODS OF CONSTRUCTION IN SPECIFIC CITIES ARE REVEALED WHEN A WIND EVENT OCCURS. Roof framing schemes involving only rafters are traditional in Plainview, Texas; this construction procedure invites failure of entire roof segments.

FIGURE 53. PARTIALLY BURIED CONCRETE BLOCK PERIMETER FOUNDATIONS ARE
TRADITIONAL IN OMAHA, NEBRASKA. The Omaha Tornado of May
6, 1975 pushed many houses off the perimeter walls.

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FIGURE 54. THE ENTIRE SUPERSTRUCTURE UNIT OF THIS HOUSE HAS BEEN MOVED LATERALLY. The traditional method of construction in Omaha contains no foundation anchorages which will resist this motion. .

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FIGURE 55.   RELATIVELY LOW WINDSPEEDS MOVED THIS OMAHA HOUSE FROM ITS FOUNDATION.
This superstructure to foundation anchor detail had become traditional
in the Omaha area.

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Observations of housing damage also suggest that houses with porches
or large overhanging eaves which face the wind and houses oriented
so that gables face the approaching wind are more vulnerable to wind
than similar houses in other orientations.

The houses illustrated in Figure 56 were damaged by the
Plainview, Texas Tornado of April 15, 1973. Note that the houses
along the west side of the street are severely damaged, and that the
failure mode suggests that damage began in the garage area. Garage
doors, especially double doors (a single door for a two car garage),
offer little resistance to wind-induced forces as they are easily
pulled from the supporting tracks or fail in flexure. (It should be
obvious that a garage door is weaker than a residential wall of com-
parable size.) Once the door fails, air fills the structure and ex-
treme outward and upward acting pressures act to fail roofs and walls
of the house. A house in the lower part of Figure 48 also exhibits
this failure mode. Figure 57 is an aerial photograph of a housing
area in Xenia, Ohio which experienced a tornado on April 3, 1974.
Houses with westward-facing garages experienced greater degrees of
damage than similar housing which was oriented differently.

Failures initiated because of porches, overhanging eaves,
or gables which faced into the wind are illustrated in Figure 58,
and roof damage associated with a porch can be observed in the lower
part of Figure 48. Often, failures initiated at these points lead
to complete destruction of the house.

3. House Geometry

Hip and mansard roofs appear to offer better wind resistance
than gabled and flat roofs (Fig. 59). This observation is shared
by Walker (1975) and by Kiesling (1975). In addition to their favor-
able shape from an aerodynamic point of view, these types of roofs
have better anchorage, as the roof is tied to the wall around the en-
tire perimeter of the house. Figure 60 shows two houses, side-by-side,
in McComb, Mississippi. Clearly, the house with the hip roof has sus-
tained significantly less damage than the house with the gabled roof.
Another example was observed in the Plainview, Texas Tornado of
April 15, 1973. The house in the center of Figure 61 had significantly

FIGURE 56. THREE HOUSES AFFECTED BY THE PLAINVIEW TORNADO OF APRIL 15, 1973.
The houses on the right and left had garages which faced eastward
and were damaged severely, while the house in the center had a
garage which faced northward.

FIGURE 57. ORIENTATIONS OF GARAGE DOORS ARE RELATED TO SEVERITY OF HOUSING DAMAGE. These houses in Xenia, Ohio were damaged more severely if their garages had a westward orientation (north is to the left).

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FIGURE 58.
PORCHES, OVERHANGING EAVES, AND GABLES WHICH FACE THE APPROACHING WIND OFTEN ARE FAILURE INITIATION POINTS. These houses in McComb, Mississippi had eaves extending beyond gables.
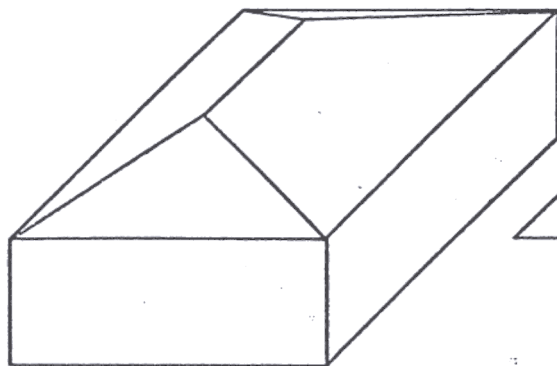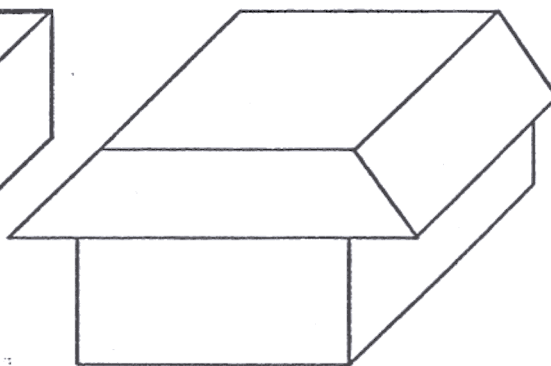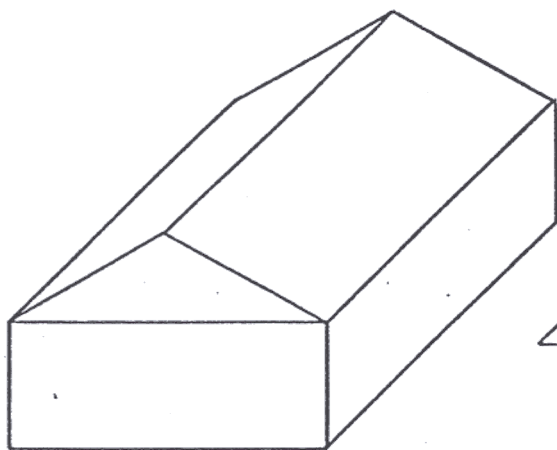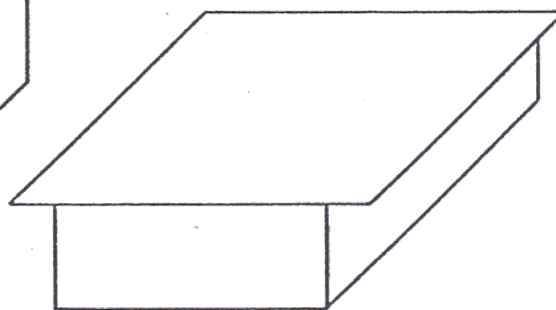
FIGURE 59. DIAGRAMS OF ROOF GEOMETRIES COMMON TO HOUSING.
Hip and mansard roofs seem to fare better in
windstorms than gable and flat roofs.

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FIGURE 60. ROOF GEOMETRIES SEEM TO INFLUENCE THE SEVERITY OF DAMAGE EXPERIENCED BY HOUSING. The house with a hip roof (right) sustained less damage than the house with the gable roof (left) in McComb, Mississippi.

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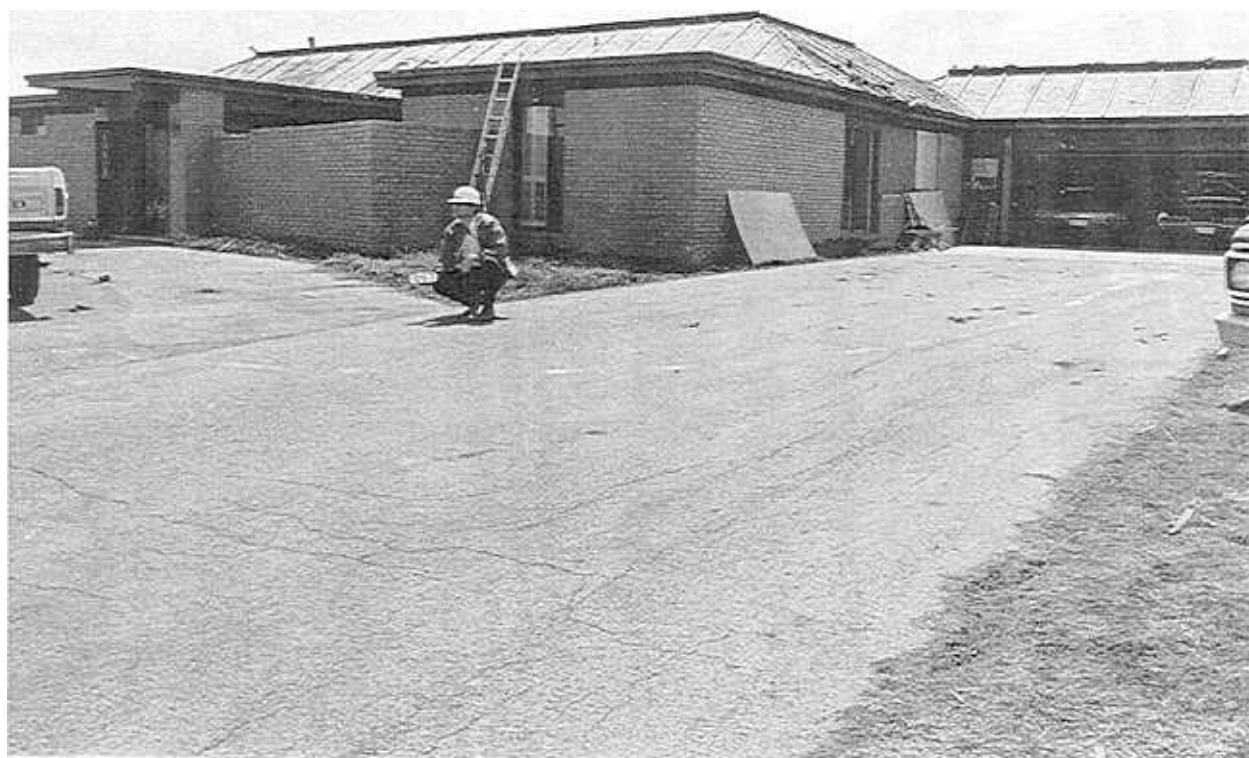
FIGURE 61. THE MANSARD SHAPE OF THE ROOF OF THIS HOUSE MAY HAVE IMPROVED ITS RESISTANCE TO WIND. The family did not move out of this house, while families on either side had to relocate because of severe damage to gable roofs.

less damage than the houses on either side. The superior performance was attributed to the mansard shape of the roof and a unique scheme for anchoring the roof to the walls (Fig. 62).

4.   Shielding of Houses

In residential areas where many large trees are present, houses receive considerable shielding from damaging winds because of trees. Shielding by trees has also been observed in certain mobile home parks (Fig. 63). Louisville, Kentucky was struck by a devastating tornado on April 3, 1974. Wind damage in the older section of town which had large trees was considerably less severe than wind damage in a new section of town where trees were small or were nonexistent. The adverse effects of trees are that they sometimes become uprooted and fall on houses, causing considerable localized damage.

The mutual shielding effects afforded by a group of houses is a recognized, but not too well-understood, effect. Clearly, single houses in the open (such as rural houses) and houses at the edge of a group of houses would feel the full effects of a windstorm. This effect was demonstrated in the cyclone which affected Darwin in the Northern Territory of Australia on December 25, 1974 (Walker, 1975). For houses in the interior of a group, there are effects which mitigate, as well as effects which may accentuate, damage. It seems clear that effects of a tornado would be less severe near the ground as it moves into a housing area because of the increased roughness of the surface. It also seems reasonable that individual houses may gain by being shielded by adjacent houses. On the other side of the issue are two effects which work in an opposite direction -- wake turbulence and missiles. Severe turbulence downstream from a structure in a windfield may impinge upon a house in a fashion which brings about failure. Furthermore, missiles from a house which fails in a windstorm may impact upon houses downwind, thus causing openings which might provide a failure initiation point. This latter effect was a dominant cause of failure in Cyclone Tracy (Walker, 1975) and has been observed in tornado damage (Fig. 64). In the Plainview, Texas Tornado of April 15, 1973 a portion of a house with a windward facing garage flew across the street and five houses down the

FIGURE 62. THE FRAMING PLAN FOR THE MANSARD ROOF IN FIGURE 61 INCLUDED A UNIQUE DETAIL. Wall studs extended through the top plate to form the end vertical member in the mansard truss.

FIGURE 63.   TREES AFFORD SOME PROTECTION FROM WIND.   The mobile
             homes in the trees (left) sustained less damage than
             those in the open (right) during the Hereford, Texas
             Tornado of April 19, 1971.

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FIGURE 64.   THE ISOLATED HOUSING DAMAGE WAS CAUSED BY DEBRIS IMPACTING FROM A
FAILING HOUSE ONE-HALF BLOCK AWAY. The Plainview, Texas incident
is a classic example of missile-induced failure.

block to damage a house that otherwise would, probably, have remained
undamaged. In this case, the tracing of the debris causing the fail-
ure to its original location precluded erroneous conclusions from aerial
photograph data regarding "skipping" tornadoes.

5. Terrain

While it is reasonable to expect a mitigation of tornadic
effects in hilly terrain or in a valley, some recent tornado events
have shown that terrain undulations do not necessarily afford pro-
tection from tornadoes. Many of the tornadoes of April 3-4, 1974 had
very long tracks, some of which followed very hilly terrain (Fujita,
1975). The Omaha Tornado of May 6, 1975 followed the rough, built-up
terrain within the city very closely. Severe damage to housing occur-
red both on the front and rear sides of hills, with respect to the
direction of tornado travel (Fig. 65).

C. Missile Events in Housing Areas

Conventional residential walls are susceptible to perforation
by tornado-generated missiles even if a brick or other masonry ve-
neer is used for exterior cladding. Figure 66 illustrates a resi-
dential wall that has been perforated by a large timber missile that
was attached to a carport roof. This missile, which was generated
in the Plainview, Texas Tornado of April 15, 1973, consisted of two,
2 X 12 in. (51 X 305 mm) timber beams joined together by a 5/16 in.
(7.9 mm) steel plate. The missile penetrated the wall and extended
approximately seven feet inside the house.

Pieces of timber such as 2 X 4 in. (51 X 102 mm) planks nor-
mally will not penetrate a residential wall although they may gain
entry into the house through windows and doors. Additional examples
of missiles which impact upon houses are illustrated in Figure 67.
Missiles can sometimes be carried high into the air by the tornadic
winds and then perforate residential roofs as the missile falls back
to the ground. Figure 68, taken following the Burnet, Texas Tornado
of March 10, 1972 illustrates a missile which perforated a residential
roof.

FIGURE 65.   TORNADOES CAN FOLLOW THE TERRAIN VERY CLOSELY.
The Omaha Tornado of May 6, 1975 caused severe
damage in valleys between hills.

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FIGURE 66.   MISSILES ARE MAJOR FACTORS IN INDUCING DAMAGE TO HOUSING.
The large beam shown here was attached to a carport roof
which became airborne.

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FIGURE 67.   EXAMPLES OF TORNADO-GENERATED MISSILES IN RESIDENTIAL AREAS.
Many missiles in Omaha, Nebraska penetrated exterior walls
(top) while some missiles in Plainview, Texas entered the
house (below).

FIGURE 68. MISSILES CAN BE CARRIED TO GREAT HEIGHTS AND DROPPED ON HOUSES.
This missile perforated a residential roof from above in
Burnet, Texas.

D. Structural Integrity of Housing

The most important consideration in building wind resistance
into a house is that the overall integrity of the structure should
be maintained. The roof should be securely anchored to the walls.
The walls should be tied securely to the foundation. If either of
these anchorages fail, then progressive failure can take place.
For example, if the corner of a roof is lifted by the winds, air
pressure can build under the roof causing large uplift forces.
If the roof is lifted completely off of the structure, the walls
have lost most of their support. They are then likely to collapse,
usually outward, as interior partitions may prevent them from
falling inward. Figure 69 shows the remains of a house following
a tornado in Burnet, Texas in 1972. The roof and walls are com-
pletely gone as a result of a progressive type of failure described
above. Figure 70 shows a duplex in McComb, Mississippi. Here the
roof was adequately anchored by means of "hurricane clips" and the
integrity of the structure was maintained. If properly installed,
these connection systems provide adequate anchorage in winds up to
125 mph (56 m/s) or more.

Brick veneer is often pulled from stud walls because of inade-
quate anchorage. Metal ties are normally provided to tie the brick
veneer to the stud walls. These metal ties are nailed to the studs
and are bonded into the mortar joint. Outward acting wind forces on
side and leeward walls tend to pull the veneer wall away from the
stud wall. Atmospheric pressure change could also contribute to the
initiation of such a failure, although enough venting area is usually
present in the wall detail though "weep holes" and through openings
to the top.

Unless the roof anchorage is carried to the foundation through
the walls, extensive damage or collapse of the residence can still
occur. The residence shown in Figure 71 was well built and maintained
its structural integrity even though the roof was blown away. How-
ever, inadequate anchorage to the foundation allowed the winds to carry
this house more than 100 ft (31 m) from its original location.

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FIGURE 69.   HOUSES ARE OFTEN DAMAGED THROUGH PROGRESSIVE FAILURES AFTER A
WEAK COMPONENT IS REMOVED.   The walls of this house fell out-
ward after the roof was removed.
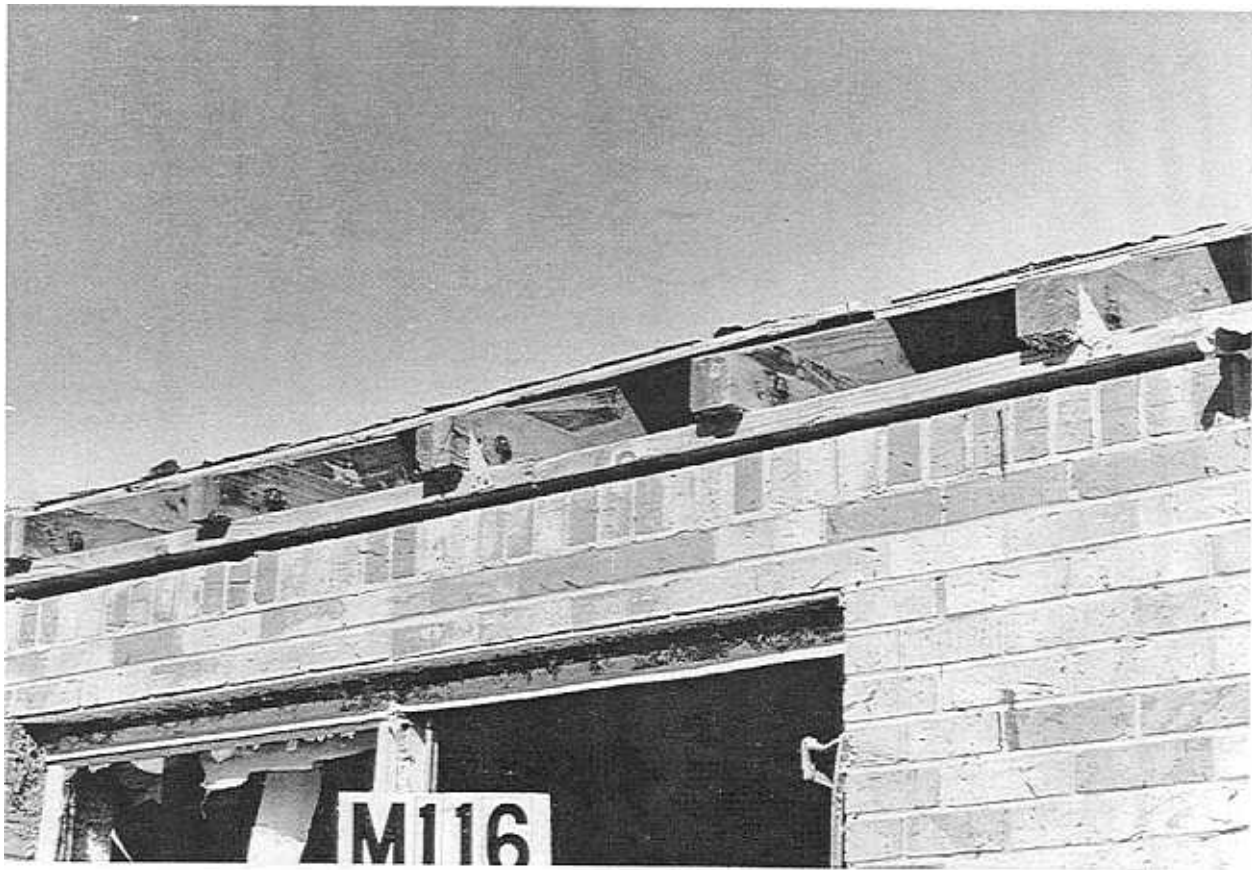
FIGURE 70. HURRICANE CLIPS CAN BE INSTRUMENTAL IN REDUCING THE
SEVERITY OF DAMAGE. The clips along the wall plate
hold the rafters to the walls.

FIGURE 71.   THE HOUSE WAS MOVED FROM THE BLOCK FOUNDATION (FOREGROUND)
            TO ITS FINAL POSITION 100 FT AWAY.   The roof was removed
            but the superstructure retained its integrity.

E Occupant Safety in Houses

For occupant safety a basement or an above ground inresidence shelter affords the best protection from tornadoes and other extreme windstorms. An inresidence shelter is preferred to an outdoor storm cellar because of the danger and inconvenience of getting to an outdoor shelter during bad weather (Kiesling and Goolsby, 1974). Many people have been seriously injured or killed by flying debris while trying to reach an outdoor storm cellar during a windstorm.

If a basement or inresidence shelter is not available, interior rooms,closets, bathrooms or hallways provide the best protection during a tornado. Persons should stay close to the floor and should get under heavy furniture or tables if possible.

When seeking shelter in a basement, consideration should be given to the possibility of debris falling into the basement if the house above is totally destroyed. Deaths have occurred in basements from drowning when occupants were trapped under debris and water lines failed. Although fire is rarely a danger following a tornado, the presence of broken gas lines and broken power lines pose some threat of fire, particularly to someone trapped in a basement.

VII   ATMOSPHERIC PRESSURE CHANGE

A.   The Pressure Change Phenomenon

Popular concepts of tornadoes award substantial attention to
the "pressure drop" attendant to tornadoes, and attribute many build-
ing failures to the pressure change phenomenon. These concepts often
refer to the change in pressure as "near vacuum" or "very low," thus
implying pressure changes of a half-atmosphere or more. Unfortunately,
some of our basic reference works contribute to these popular concepts
by describing pressure change through such descriptive, but relative,
terms as "great drop" (American Peoples Encyclopedia, 1965), "extremely
low" (Lincoln Library, 1969), "extremely sharp pressure decrease," and
"strong pressure differences over large areas" (Halsey, W. D. ed., 1976).

Most researchers of tornadic phenomena agree that actual atmospheric
pressure changes are relatively small. Davies-Jones and Kessler (1974)
summarize measured pressure deficits in tornadoes as recorded by both
official weather stations and citizens. They note that the reliability
of citizens' readings can be questioned because they are usually taken
under conditions of great stress. The largest reported value is 192 mb
(about 2.8 psi), or less than 20 percent of an atmosphere. Official
recordings, usually taken automatically, reflect smaller values (less
than 20 mb deficit) when tornadoes cross weather stations. The often
used cyclostrophic equation permits pressure deficits to be calculated
by assuming a tangential windspeed vs. radius relationship (usually
a Rankine Vortex) and a maximum wind velocity. Values of tornadic
windspeed which approach the currently perceived upper limit (Ref.
Section IV) do not produce pressure deficits which exceed .2 atm
(200 mb) using these methods, which assume classic vortex flow. Hence,
it would appear that pressure change of .2 atm (approximately 3 psi)
would be a limiting value, with values near the ground in most torna-
does being much smaller.

B.   Assessment of Atmospheric Pressure Change for Engineering Use

Where engineered structures are concerned, a rational assessment
of the pressure change phenomenon suggests that pressure change may
play a minor role in the damaging mechanism. Several factors contribute

to this observation. First, while theoretically derived pressure change values can be potentially damaging (approaching 3 psi; 200 mb), it is reasonable to expect that pressure change values near the ground (where the vortex is not in cyclostropic balance) are different. Secondly, a large percentage of all tornadoes possess windspeeds of far less magnitude than the maximum value; thus, attendant pressure changes would be much smaller than those associated with severe tornadoes. Finally, the translational speed of tornadoes is such that, for most conventional building situations, venting could be expected to relieve tendencies for significant internal pressure increases as the tornado approaches the building.

To illustrate the latter point, consider the approach taken in the development of design criteria for shelters in schools (DCPA, 1975). A windspeed of 260 mph (116.2 m/s) was selected as design value. This value for maximum wind represents a wind condition more severe than that associated (through the Fujita Scale) with 98 percent of all tornadoes of record. The attendant pressure change for this tornado is 1.42 psi (95 mb) [assuming a translational velocity of 60 mph (26.8 m/s) and a radially directed wind component equal to one-half of the tangential component; see vector diagram, Table V]. The design basis tornado is assumed to be of an average diameter and possess an above average translational velocity (60 mph; 26.8 m/s) such that the change in pressure will occur in as little as three seconds.

The approach taken in using this design basis tornado to develop criteria for atmospheric pressure change was to determine the amount of venting area required for each 1000 cubic feet (28.3 m^3) of building volume, if the mass flow through openings is not to exceed 25 mph (11.2 m/s). In order for ambient pressure (14.70 psi; 1013 mb) to change to the reduced pressure (13.28 psi; 915 mb) the air volume must increase. This increased volume of air must be vented. Recognizing, for assumed isothermal conditions, that

$$P_1 V_1 = P_2 V_2$$

where P_1 = ambient pressure [14.7 psi (1013 mb) in example]

P_2 = pressure in tornado [13.28 psi (915 mb) in example]

V_1 = original volume [1000 cu ft (28.3 m^3) in example]

V_2 = volume of air associated with reduced pressure

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the amount of air that must be evacuated from a 1000 cubic foot room is

$$V_2 - V_1 = \frac{P_1 V_1}{P_2} - V_1 = 106.9 \text{ cu ft } (3.03 \text{ m}^3)$$

If the air is to be vented in as little as three seconds, the flow rate through openings must be

$$Q = \frac{V}{t} = 36.9 \text{ cu ft/sec } (1.05 \text{ m}^3/\text{s})$$

To keep mass flow below 25 mph (11.2 m/s), the area of the vent must be

$$A = \frac{Q}{V} = \frac{(36.9)}{25} \times \frac{(3600)}{(5280)}$$

$$A = 1.006 \text{ sq ft}/1000 \text{ cu ft } (.33 \text{ m}^2/100 \text{ m}^3)$$

In this analysis, one square foot of venting area per 1000 cu ft of volume (or 1/3 square meter per 100 cubic meters of volume) would be adequate to effectively vent a building which experiences the design basis tornado. Most houses and many commercial buildings have this amount of venting area through air conditioning systems, exhaust fans, attic doors, etc.

Another useful perception of pressure change effects on buildings relates to the magnitudes of wind induced pressures and atmospheric pressure change induced pressures. Maximum values of wind induced pressure (sometimes referred to as "dynamic pressure") and atmospheric pressure drops accompanying the vortex do not occur simultaneously on a building component, at least for most assumed tornado vortex models. Thus, the engineering problem becomes one of ascertaining which type of pressure change has the maximum effect on the building component at issue. Comparisons of the relative magnitudes of the two types of pressure change can only be accomplished when a specific design tornado, a specific building, and a specific building component are considered. Tornado properties, building geometry and venting conditions influence dynamic pressure and atmospheric pressure change calculations; hence, care must be exercised in making generalizations regarding relative effects. A sealed building, one-story in height will experience both types of pressure change.

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Table V summarizes the net outward acting pressure induced by each phenomenon on the roof of such a structure (if the roof is flat) for various assumed maximum windspeeds and other tornado properties.

TABLE V

COMPARISONS OF PRESSURE CHANGES INDUCED BY WIND
AND ATMOSPHERIC PRESSURE CHANGE ON A ROOF OF A SPECIFIC
BUILDING AND A SELECTED DESIGN BASIS TORNADO

Maximum Wind Velocity, mph (1) $V_{ro}+V_t$	Rotational Wind Velocity, mph (2) V_{ro}	Tangential Wind Velocity mph (3) V_θ	Pressure due to Atmospheric Pressure Change, psf (4)	Uplift Pressure on Roof, psf (5)
100(44.7 m/s)	50(22.4 m/s)	45(20.1 m/s)	10.1(.484 kPa)	17.9(.857 kPa)
150(67.1 m/s)	100(44.7 m/s)	89(39.8 m/s)	40.3(1.930 kPa)	40.1(1.920 kPa)
200(89.4 m/s)	150(67. m/s)	133(59.5 m/s)	90.7(4.343 kPa)	71.7(3.433 kPa)
250(111.8 m/s)	200(89.4 m/s)	178(79.6 m/s)	161.3(7.723 kPa)	112.0(5.363 kPa)

Wind velocity with respect to ground reference.

Assumes 50 mph (22.4 m/s) translational velocity (V_t).

Assumes radial component of wind velocity is one-half of tangential velocity ($V_r = \frac{1}{2} V_\theta$).

Based on integration of cyclostrophic equation and Rankine Vortex; also assumes sealed building

Assumes flat roof and uplift pressure coefficient of 0.7 (ANSI, 1972).
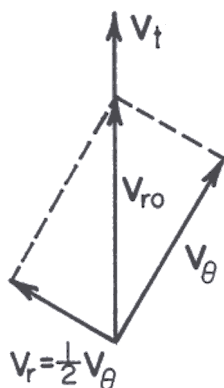
$$V_{ro}^2 = V_r^2 + V_\theta^2$$

$$V_{ro} = \left(\frac{1}{4} V_\theta^2 + V_\theta^2\right)^{\frac{1}{2}}$$

$$V_\theta = 0.894\, V_{ro}$$

VIII. TORNADO-GENERATED MISSILES

A. Importance of Missile Analysis

Tornado-generated missiles are important to structural engineers designing buildings for protection of people and property. Tornado-generated missiles range in size from small objects such as roof gravel and twigs to large objects such as automobiles and storage tanks. The most common missiles observed in tornadoes are pieces of wood from the roofs and walls of destroyed houses. Wall board, insulation, and sheet metal are also common missiles. Figure 72 illustrates the size, range and character of tornado-generated missiles.

Many tornado deaths and injuries can be attributed to tornado-generated missiles. Persons in the open, including those in the process of seeking safety in outdoor shelters, are susceptible to injury or death from windborne missiles. A person should seek shelter in an interior room or closet, rather than going outdoors to an underground shelter, if storm conditions indicate that the occurrence of a tornado may be imminent. (See discussion of tornado shelters in Section VI.E)

B. Missile Action in Tornadoes

There are a number of factors that affect missile flight trajectories in a tornado. These factors include the injection mechanism, missile characteristics, the location of a missile relative to tornado path, the initial elevation of missile, and the degree of anchorage.

Before a missile can "fly" within the tornadic windfield, it must somehow be injected into the windstream. Various injection modes are possible. Injection modes include aerodynamic, ramp, and explosion mechanisms (Fig. 73). As the air flows over a potential missile, aerodynamic lift forces may develop. When these forces exceed the weight of the object, the object accelerates in a vertical direction and becomes airborne. This mode of injection is referred to as "aerodynamic" injection. The duration of the initial lift force is relatively short -- usually less than a second -- but may vary considerably with changes in tornado translational speed, maximum windspeed, and windfield geometry. Once the object has been lifted off the ground, the upward component of the wind velocity

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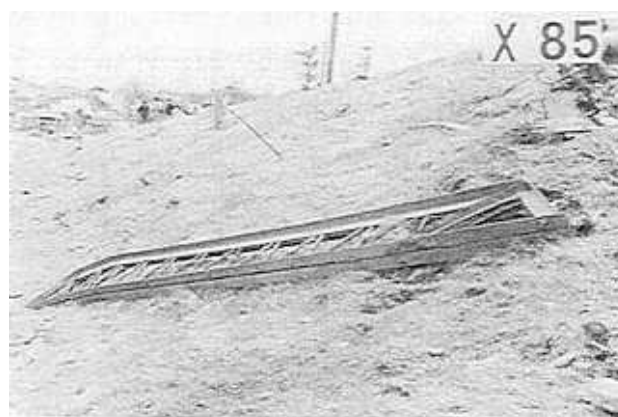
FIGURE 72.   TYPICAL TORNADO-GENERATED MISSILES.   Missile sizes
range from splintered boards to heavy beams and
trusses.

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AERODYNAMIC INJECTION

RAMP INJECTION

EXPLOSION INJECTION
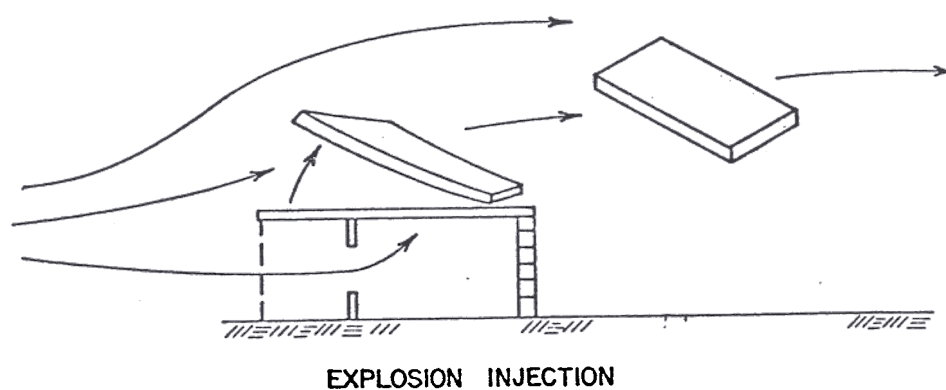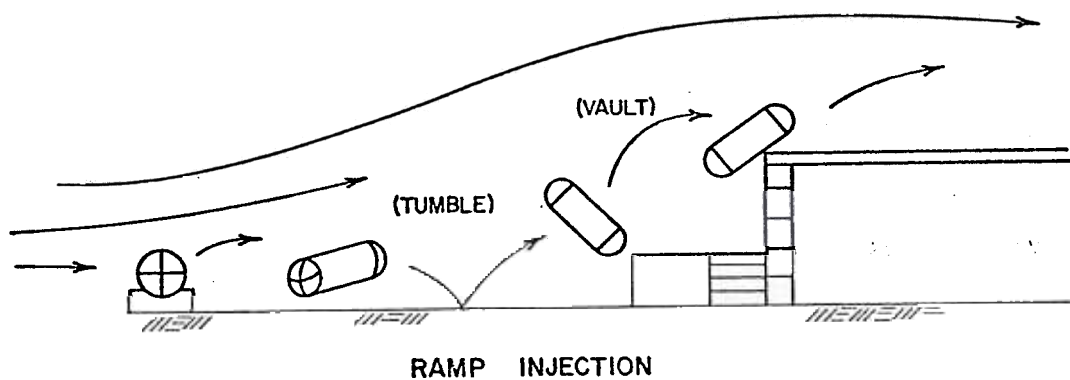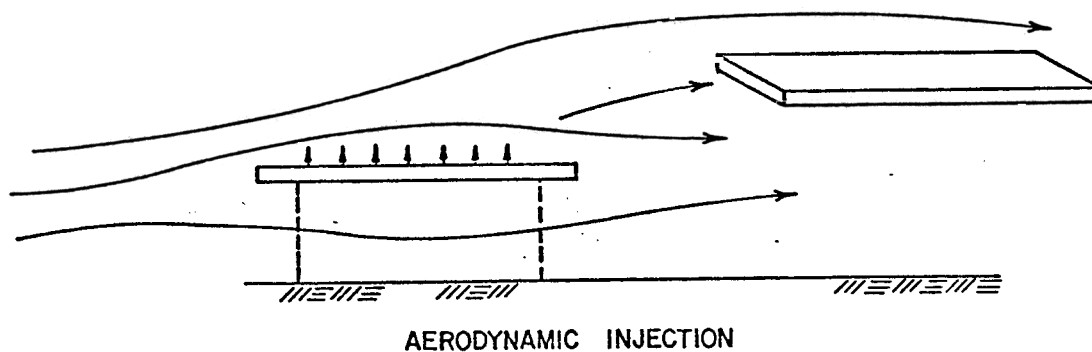
FIGURE 73. MISSILE INJECTION MECHANISMS. Once airborne, vertical components of air motion can sustain the missile until significant horizontal velocities are attained.

vector helps to sustain the missile in flight. In some instances
the missile may not become airborne, but may roll or slide along
the ground. If it then encounters an incline it may be injected
into the windfield. This injection mode is referred to as "ramp"
injection. Occasionally, a missile will be injected into the wind-
field by upward forces attendant to building failure as a building
comes apart in the face of wind action. This injection mode is
referred to as "explosion" injection.

In addition to its weight, shape, and size, the aerodynamic
characteristics of an object affect the ability of a missile to be
transported in a tornado. Missiles have six degrees of freedom of
motion (three translational and three rotational); these, in turn,
imply six types of aerodynamic drag or lift coefficients. Very
little is known at this point in time about the six degree-of-freedom
behavior of missiles in tornadic windfields. Research is currently
in progress to define these coefficients using wind tunnel technology.
Related to this same problem is the need to define, experimentally,
limiting values of these coefficients so that the upper bound of
missile velocity, relative to tornado wind velocity, can be established

A crude measure of the tendency of an object to "fly" in a tor-
nado windfield is given by its flight parameter:

$$P_F = \frac{C_D \, A}{W}$$

where

C_D = aerodynamic drag coefficient (dimensionless

A = surface area exposed to the wind, ft^2

W = weight of the object, lb

The larger P_F is, the more likely the object is to fly in a tornadic
storm.

Values of C_D for various objects are not known precisely. This
lack of knowledge has led to considerable controversy in the prediction
of tornado missile flight trajectories in the nuclear power industry.
In reality, a missile tends to tumble in the windfield and, thus, a
single value for C_D is not appropriate. As the missile tumbles
because of turbulence or aerodynamic instability, different sides of

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the missile are exposed to the wind vector. Therefore, the value of C_D is a function of time, orientation of the missile and orientation of the wind velocity vector. The area used in the expression for P_F is taken as the largest projected surface area.

Table VI lists flight parameter values P_F for a variety of potential tornado missiles. The purpose of the list is primarily for comparison purposes. The values of C_D, which are somewhat dependent on Reynolds Number, are based on an assumed wind velocity of 200 mph (89.4 m/s).

The missiles in the table are listed in descending order of flight parameter value. Thus, the objects at the top of the list are more likely to "fly" than the objects below, all other conditions being equal. Included in the list are six general types of missiles. These include:

( )   Roof gravel, brick, block

(2)   Sheet metal, plywood, roof sections

(3)   Various sizes of timber missiles, including utility poles

(4)   Various sizes of steel pipe

(5)   Steel tanks

(6)   Trailers, mobile homes, campers, autos, iron and buses.

It should also be pointed out that the flight parameter applies to the object once it is airborne. How the missile is injected into the windfield is another matter.

C.   Missile Impacts on Structures

The impact of a tornado-generated missile upon a building causes damage by two principal mechanisms. Local impact involves penetration (missile damages but does not pass through the barrier) or perforation (missile passes through the barrier). Examples of these missile impact phenomena are illustrated in Figure 74. In the case of concrete and masonry the impact of a missile can also cause local spalling of particles from the back side of the barrier, even though the missile does not penetrate or perforate the barrier. Spall particles can cause extensive damage to contents of the building or injury to building occupants. To be damaging, the missile must strike a wall "end-on" (or almost "end-on") at least within a relatively narrow angle with a line

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TABLE VI

FLIGHT PARAMETERS FOR POTENTIAL TORNADO MISSILES

Missile	C_D	Max. A $(ft.^2)$	W (1b.	$\dfrac{C_D A}{W}$	Comments
Sheet Metal (2' x 8' x 18 gage)	1.2	16.00	34.9	0.550	
Plywood Sheet (4' x 8' x 3/4")	1.2	32.0	96.0	0.400	
Timber Wall Stud (2" x 4" x 12')	1.5	3.6	19.6	0.277	
Roof Section (10' x 12' with 3/4" Sheathing and 2" x 6" rafters)	1.2	120.0	614.0	0.235	Represents a large section of residential roof
Lightest Mobile Home (8' x 40' @ 15 psf)	2.0	320.0	4800.0	0.133	
Camping Trailer (7' x 7' x 23')	2.0	161.0	2500.0	0.0537	Does not include tractor
Timber Fence Post (4" x 4" x 6')	1.5	1.81	21.9	0.124	Fence post
Single Brick (T 5/8" x 3 5/8" x 7 5/8")	2.0	0.19	3.1	0.124	Not attached to wall
Timber Beam (4" x 12" x 12')	1.3	11.5	139.0	0.108	
Older Mobile Home (10' x 48' @ 20 psf)	2.0	480.0	9600.0	0.100	
U-Haul Trailer (5' x 5' x 8')	2.0	40.0	1000.0	0.080	
Roof Gravel (0.75" diam)	0.5	0.0031	0.0192	0.080	
Newer Mobile Home (12' x 60' @ 30 psf)	2.0	720.0	21,600.0	0.0667	
Semi-Trailer (8 1/2' x 8' x 40')	2.0	340.0	12,000.0	0.0567	Does not include tractor
Heaviest Mobile Home (14' x 70' @ 40 psf)	2.0	980.0	39,200.0	0.0500	14 ft wide
Concrete Block (7 5/8" x 11 5/8" x 15 5/8")	2.0	0.83	41.6	0.0400	Hollow block

TABLE VI
FLIGHT PARAMETERS FOR POTENTIAL TORNADO MISSILES (Cont.)

Missiles	C_D	Max. A ($ft.^2$)	W (1b.	$\dfrac{C_D A}{W}$	Comments
Compact Auto (3 1/2' x 5' x 10')	2.0	35.0	2000.0	0.0350	
Steel Rod (1" diam x 3' long)	1.0	0.25	8.0	0.0313	
Standard Auto (4' x 5' x 12')	2.0	60.0	4000.0	0.0300	
Van (6' x 5' x 12')	2.0	72.	5000.0	0.0288	
Utility Pole (13.5" diam x 35' long)	1.0	39.4	1392.0	0.0283	
School Bus (8' x 7.5' x 23')	2.0	184.0	15,300.0	0.0241	40 passenger bus assumed to be empty
Steel Tank (24" x 6'; 3/16" wall thickness)	0.38	12.0	337.0	0.025	
Steel Tank (36" x 10'; 1/4" wall thickness)	0.38	30.0	1106.0	0.019	
Steel Pipe (3" x 10')	0.38	2.92	76.0	0.015	
Steel Pipe (6" x 10')	0.38	5.52	190.0	0.011	
Steel Tank (120" x 40'; 1/2" wall thickness)	0.38	400.0	28,840.0	0.010	
Steel Pipe (12" x 10')	0.38	10.6	496.0	0.009	

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FIGURE 74. MISSILE IMPACT PHENOMENA. Penetration (top) and perforation (bottom) are relevant phenomena for engineers who design tornado resistant structures.

perpendicular to the wall. Otherwise the missile will glance off of the wall and do little damage.

The impact of large heavy objects usually induces failure through a mechanism called excessive structural response (Fig. 75). Structural response causes, for example, a wall panel to deform into the plastic range of material behavior and produces permanent deformation. In the case of a concrete wall, large cracks can develop in the wall if the entire wall does not fail.

D. Examples of Tornado-Generated Missiles

Several typical tornado missiles are described in the paragraphs which follow. These examples were chosen to illustrate the range of missiles that can cause damage to structures.

1. Fertilizer Tank - Lubbock, Texas

An 11 ft (3.35 m) (diameter) by 41 ft (12.50 m) (length) cylindrical fertilizer tank weighing 26,000 lbs (11794 kgf) (empty) was found approximately 3900 ft (1190 m) east of its original location following the Lubbock Tornado of May 11, 1970. The tank is shown in Figure 76 after it was returned to its cradle. The tank was essentially empty on the day of the storm, but sludge in the bottom could have added to the weight. Post-storm investigations could not establish whether the tank was airborne or if it rolled and tumbled. The exact path of travel of the tank could not be determined.

The tank rested on four steel saddles and was restrained only by its own weight. The longitudinal axis of the tank was oriented east-west. Tornadic winds pushed it off the saddle supports had moved it across relatively flat terrain (Fig. 77). It caused no damage to structures along its path, although it did cross a four-lane highway and an access road in reaching its destination. Assuming a drag coefficient C_D of 0.55 and an empty tank, the windspeed necessary to roll the tank out of the saddle support was calculated by Mehta et al. (1971) to be 183 mph (81.8 m/s). There was no opportunity to estimate the velocity achieved by the tank from field observations.

FIGURE 75. MISSILE IMPACT MAY INDUCE EXCESSIVE STRUCTURAL RESPONSE.
This failure mechanism is common in metal buildings and
masonry construction.
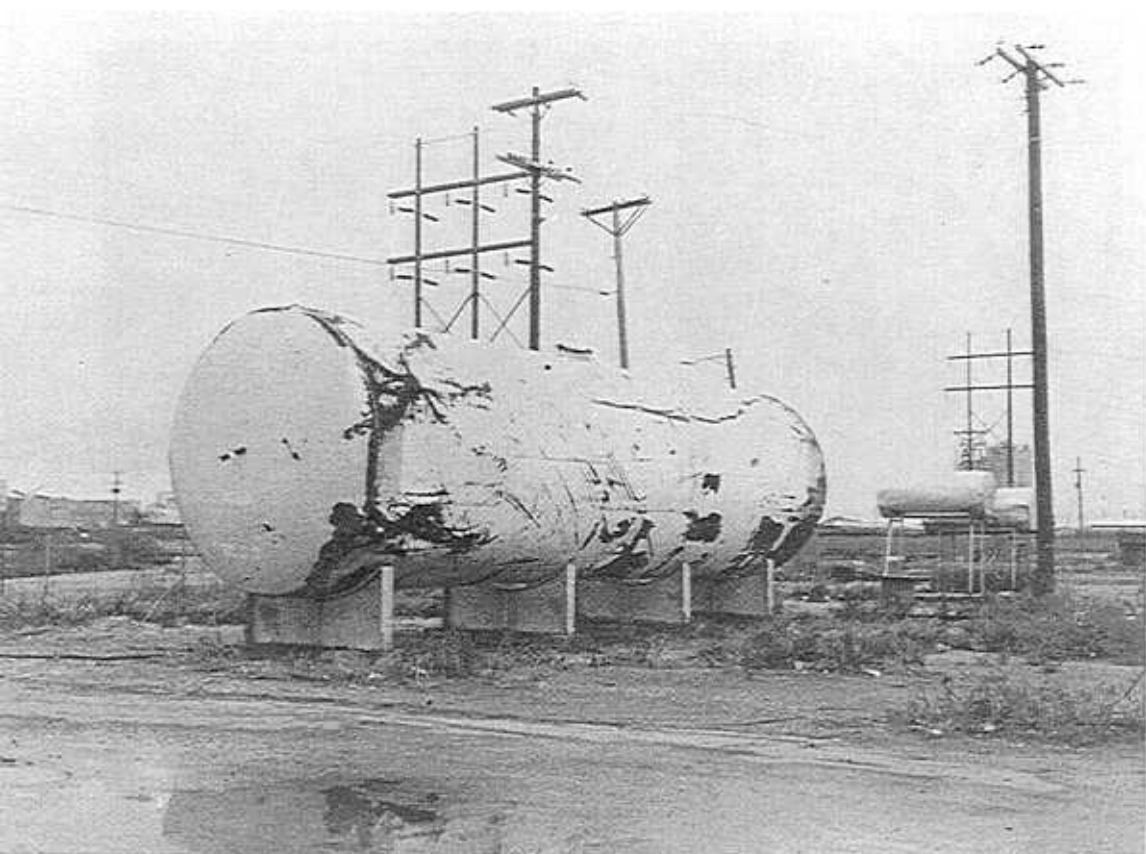
76. FERTILIZER TANK WHICH WAS MOVED 3900 FT (1190 m) BY THE
LUBBOCK TORNADO. The tank is shown here after it was
returned   its cradle.

FIGURE 77.   THE FERTILIZER TANK TRAVELED 3900 FT (1190 m) ACROSS
RELATIVELY FLAT TERRAIN. No ground marks were found
although it rained heavily during the storm.

2. Compressor Units - Lubbock, Texas

Three air conditioning compressor units were located on the roof of Newsom's Living Center (a one-story, light commercial building) prior to the Lubbock storm. After the storm two of the compressors were found in an adjacent parking lot while the third compressor unit impacted a second floor column of an adjacent motel (Fig. 78). No significant damage was done to the column by the impact. The weights and distances traveled for the three compressor units were:

Compressor Unit	Compressor Weight	Distance Traveled
No. 1	1100 lb (499 kgf)	170 ft (51.8 m)
No. 2	900 lb (408 kgf)	82 ft (25.0 m)
No. 3	1100 lb (499 kgf)	105 ft (32.0 m)

There was no evidence that the compressors experienced significant lift in a sense which would have made them become airborne. They were, however, torn from their anchorages by the force of the winds and moved to their final locations. Additional details of these missile events are given by Mehta et al. (1971). No attempt was made to deduce wind or missile velocities from these incidents.

3. Timber Roof Beams - Plainview, Texas

A timber missile can achieve a higher velocity prior to impact than would be predicted by its individual flight characteristics and injection mechanism, if it is originally attached to an "airfoil" such as a large roof or carport structure. An example of this type of missile was observed in the Plainview Tornado of April 15, 1973. Figure 79 shows a large beam from a carport roof. The carport was located more than a block away from the final position shown. Indications are that it flew over the house to which it was attached originally. Note that one of the carport support beams has perforated the wall of the residence. About 7 ft (2.1 m) of the beam is inside the house. The beam that perforated the wall is constructed of two, 2 x 12 in. (51 x 305 mm) timbers with a 5/16 x 11 in. (7.9 x 279 mm) steel plate between the timbers. No windspeed or missile velocity calculations were attempted for this missile.
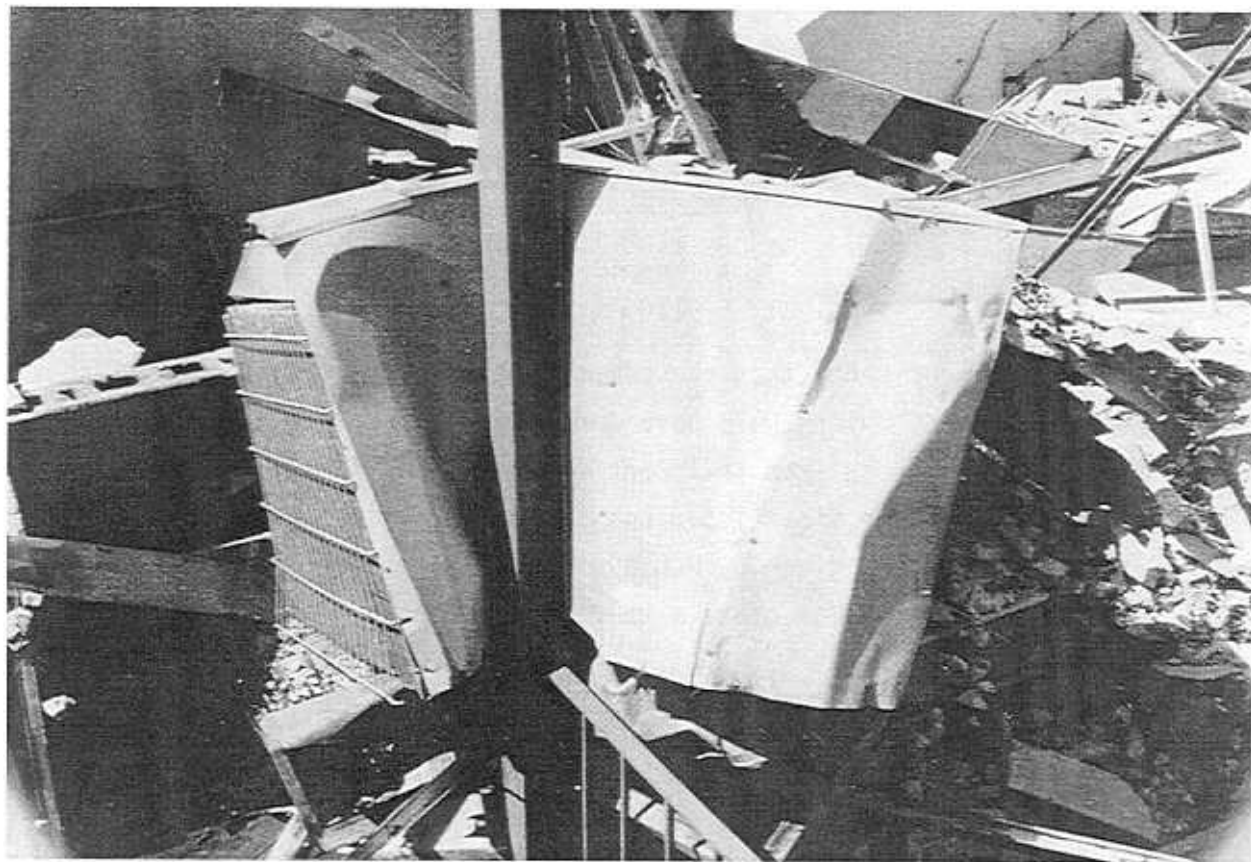
FIGURE 78. AIR CONDITIONING COMPRESSOR UNIT WHICH IMPACTED A
STEEL COLUMN DURING THE LUBBOCK STORM. The 1100 lb (499 kgf)
unit was located originally on the roof of an ad-
jacent building.

FIGURE 79.   LARGE BEAM PERFORATED RESIDENTIAL WALL IN PLAINVIEW, TEXAS.
The beam was attached originally to a carport roof which
came to rest opposite the wall shown.

4. School Buses - McComb, Mississippi

Automobiles, vans, buses, and semitrailers can, under the right circumstances, become airborne. In general, these items tend to roll and tumble along the ground. Figure 80 is an aerial view of North Pike Elementary School near McComb, Mississippi which experienced a tornado in January, 1974. Three, 40-passenger school buses can be seen in the woods nearby. At the time the tornado struck, the buses were parked in a circular drive near the entrance to the building. Investigations following the storm confirmed that these buses did indeed become airborne. There is an 8-ft embankment along the drive next to the woods (Fig. 81). There were no ground marks to indicate that the buses had rolled or tumbled up the embankment. The buses were unoccupied at the time of the tornado. The tornado moved from left to right in the photograph. The buses were located on the right-hand side of the tornado path at the approximate radius of maximum winds.

5. Utility Pole - Xenia, Ohio

The utility pole shown in Figure 82 traveled approximately 160 ft (48.8 m) in a NEE direction from the point where it was broken from its foundation. The pole is 25 ft 6 in. (7.77 m) long and is 10 in. (254 mm) in diameter. Investigators could not determine if the pole tumbled, rolled or flew from its original position. The wire evidently severed at the time the pole was broken from its support. Wires attached to utility poles often restrain the poles and prevent them from traveling very far. In any event, the presence of wires makes analysis of poles and transmission towers very difficult.

E. Examples of Objects That Did Not Become Missiles

Questions regarding the types of missiles that can be expected in a tornado can best be answered by examining storm damage records such as those described above. Beyond this preferred approach are two additional methods: (1) analysis and (2) observations of objects which had opportunities to become missiles but did not. The analysis approach requires knowledge of windspeeds that can actually occur in a tornado and upper-bound values for drag coefficients. Neither of these factors is known presently with an acceptable degree of confidence; hence, the analysis approach has not proven
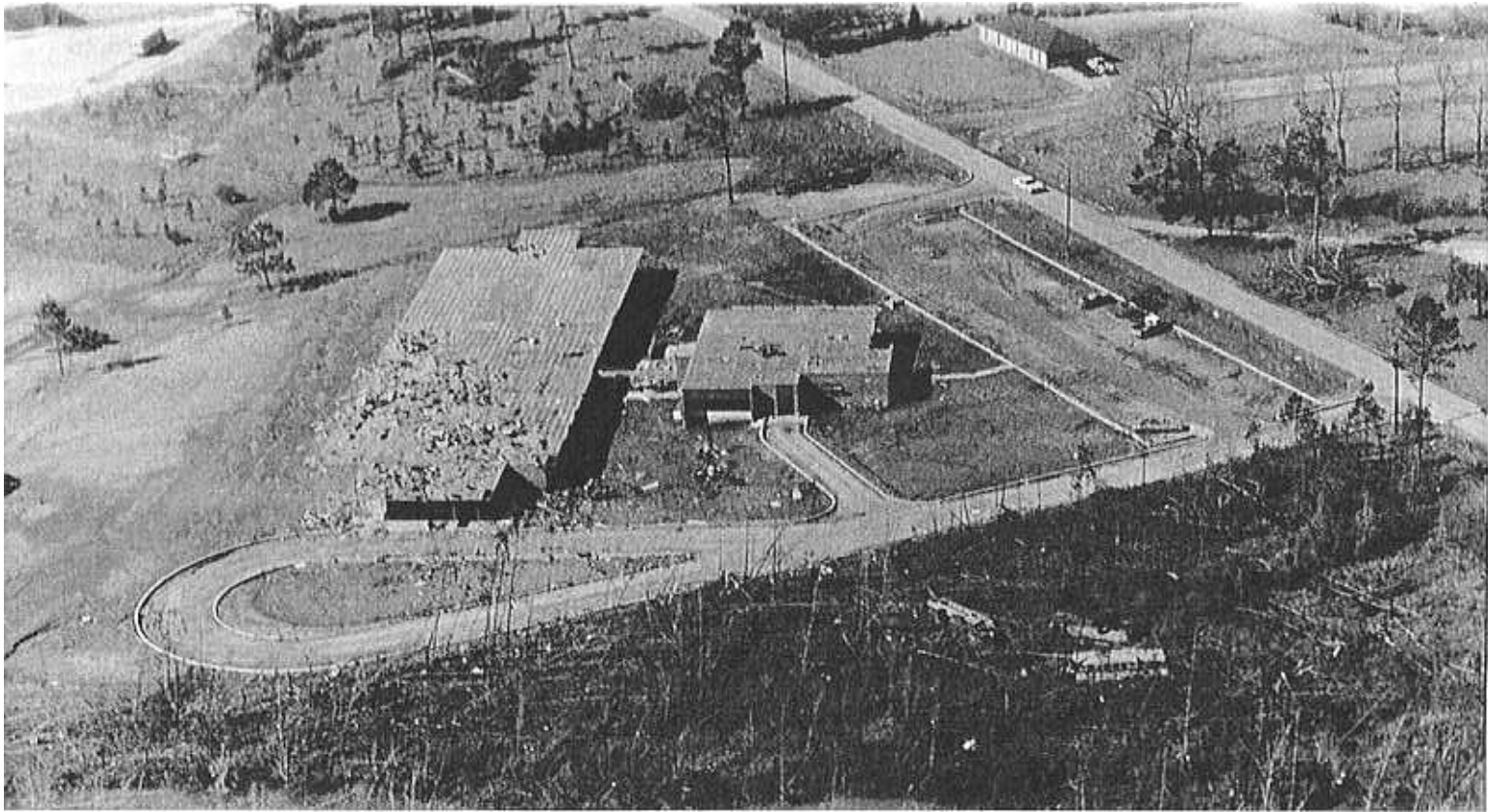
FIGURE 80.   BUSES AT NORTH PIKE ELEMENTARY SCHOOL IN McCOMB,
             MISSISSIPPI WERE MOVED BY A TORNADO ON JANUARY 10,
             1974. Originally parked in the circular drive at
             left, the three buses moved to lower right by
             passing over an 8-ft (2.44 m) embankment.

FIGURE 81.   THE 8-FT EMBANKMENT OVER WHICH THE McCOMB,
             MISSISSIPPI SCHOOL BUSES (FIG. 80) PASSED.
             The buses were probably airborne as they
             passed the embankment.

FIGURE 82. UTILITY POLE IN XENIA, OHIO TRAVELED 160 FT (48.8 m)
DURING APRIL 3, 1974 TORNADO. Power and anchor lines
usually restrain poles of this type to their immediate
location.

satisfactory. On several occasions, however, storm damage investigators have observed that certain types of objects did not become airborne even though intense tornadoes passed over them. Two examples of objects that did not become missiles when they had opportunities to do so are presented below.

1. Storage Yard - Brandenburg, Kentucky

The rural electric co-operative storage yard and warehouse were in the direct path of the Brandenburg Tornado on April 3, 1974. Figure 83 is an overview of the storage yard. The steel frame office and warehouse buildings seen in the background were totally destroyed. Several utility poles were stacked neatly on a rack at truck bed height prior to the storm. Most of them were removed from the rack, but simply fell to the ground without moving an appreciable distance. All of the poles on the rack were accounted for by the superintendent. A careful search of the area verified that none were missing from the yard. Other objects such as barrels and transformers of various sizes shown on the loading dock (Fig. 84) were not moved by the winds. The transformers were filled with coolant oils and, thus, were relatively heavy. The Brandenburg tornado reportedly had windspeeds exceeding 200 mph (89.4 m/s).

2. Power Plant - Washita, Oklahoma

A tornado, rated severe by personnel of the National Severe Storms Laboratory, passed over the site of a conventional gas-fired power plant near Washita, Oklahoma on April 17, 1976. Although the generating station itself sustained no appreciable damage and continued to operate under normal conditions, one of three cooling towers received significant damage to its stacks. Immediately up-wind of the power plant a pre-engineered metal building was totally destroyed. The building can be seen in Figure 85. Sheet metal cladding from the building is scattered over the entire plant site. The only building content found outside of the destroyed building was the top of a metal desk, which was carried 300-400 ft (91.4 - 122 m) at a right angle to the tornado path. An undisturbed rack of small diameter pipe can be seen in the foreground of Figure 85. Figure 86 shows a stack of larger diameter pipe that was undisturbed by the wind. A portion of the auxiliary fuel storage tank can be seen in the background of

FIGURE 83.   OVERVIEW OF BRANDENBURG, KENTUCKY STORAGE YARD
             FOLLOWING APRIL 3, 1974 TORNADO. Many objects
             which could have become airborne did not.
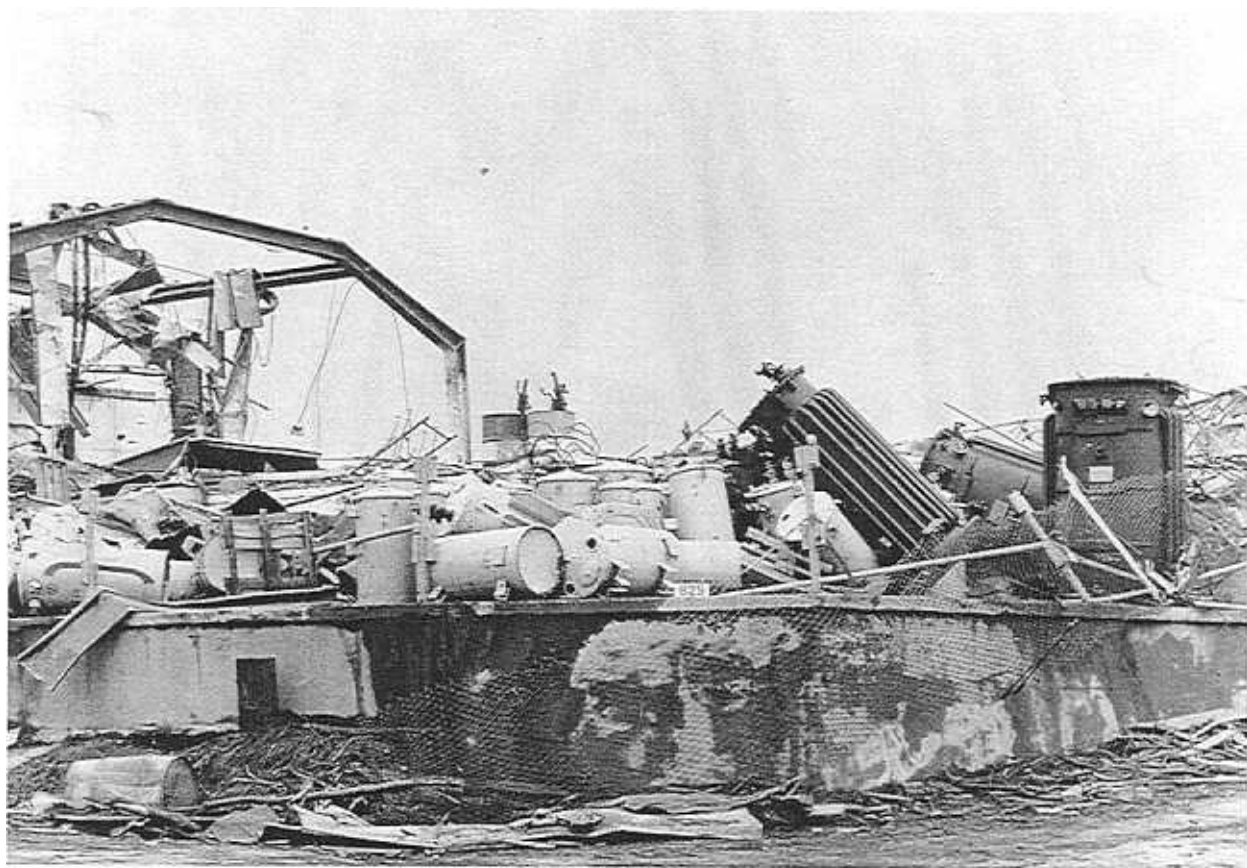
FIGURE 84. HEAVY OBJECTS SUCH AS THESE BARRELS AND TRANSFORMERS COULD HAVE BECOME AIRBORNE IN THE BRANDENBURG TORNADO. All objects of this type were accounted for in a post-storm inventory.

FIGURE 85. GENERAL VIEW OF WASHITA, OKLAHOMA POWER PLANT MAINTENANCE YARD. Pipe in foreground did not become airborne, although April 17, 1976 tornado destroyed building in background.

FIGURE 86.   LARGE DIAMETER PIPE THAT WAS UNDISTRUBED BY TORNADIC WINDS.
The Washita, Oklahoma Tornado of April 17, 1976 had an
opportunity to move this pipe.

Figure 86. This tank is immediately down-wind from the warehouse and the racks of stored pipe and equipment. There was no evidence of significant impacts on the tank from flying debris. The observation that seems appropriate from this and similar investigative efforts is that heavy material stored near ground level is not likely to become airborne in severe windstorms.

F   Missile Stories

Occasionally, stories of "incredible" missiles are recorded in the popular press and, sometimes, in the technical literature following tornado events. The object of such stories, usually, is to support concepts of incredible windspeeds in tornadoes. There have been reports of steel beams perforating the trunks of trees and of tree limbs penetrating steel beams. The familiar story of straws penetrating fence posts also falls into the incredible missile category. Investigators who have read the stories in the literature, have investigated storm damage, and have sought facts relating to reported incredible events offer three general observations. First, printed stories which relate observations of extreme missile events lack the type of data which would allow scientific analysis of phenomena surrounding the event. Second, when facts surrounding an unusual event can be established, it usually is found that the stories describing the event have been overstated, thus making the event sound more dramatic. Thirdly, many factual accounts of incredible missiles can be explained in some rational manner. Each of these observations is discussed below.

An often quoted reference for missile events is the classic book on tornadoes by Flora (1954). Flora's work is systematic and detailed, and the accounts of the tornado events contained in the text were developed from painstaking research. The missile events that are advanced, however, are presented as "reported" events, and do not contain the level of detail that would attend scientific reporting. Inclusion in Flora's book should not lead scientific investigators to conclude that all of the events are factual, but that a wide range of incidents have been "reported". The scope and nature of the events in Flora and elsewhere in the literature are intriguing and reflect a good deal of research. These incidents

have provided modern storm damage investigators with excellent guidance and perspective as they seek facts in the wake of tornado events.

Several opportunities for examining extreme missile events have been presented to storm damage investigators. A van in Omaha, Nebraska was reported to have flown over a hospital during the tornado of May 6, 1975. Field investigations showed it to have tumbled a circuitous route to its final location. The furniture vans in Xenia, Ohio (Fig. 87) were reported to have flown, full of furniture, from a parking lot, across a street, to the roof of a bowling alley. Field investigations showed that the vans were essentially empty, and tumbled (perhaps vaulted) without tractors to their final locations. A trailer loaded with sugar was reported to have been picked up and placed on the roof of a building by the Omaha Tornado of May 6, 1975. This reported event proved to be a trailer, without a tractor, which was overturned against a loading dock, with one end of the trailer resting against the wall of the building. An unknown quantity of sugar (less than a full load) was on the trailer. Finally, a report of an automobile impacting 30 feet (9.1 m) above the ground against a concrete block wall in Omaha proved to be an automobile which tumbled into a loading dock, vaulted onto the dock and came to rest against the wall.

Some factual accounts of seemingly incredible missiles can be explained in a rational manner. The most common account, perhaps, is of the "straw through the fence post". So many accounts of this phenomenon have occurred that (1) investigators were prompted to look for it in post-storm investigations and (2) scientists were moved to try to duplicate the phenomenon in the laboratory. Investigators have found some cases of straw particles on trees, fence posts, and walls. The few situations where penetration was evident involved soft wood, bark with fissures which accepted the straw, or very slight penetration. Keller and Vonnegut (1976) reported on experiments involving the propelling of broom straws into various types of wood. Straw impact velocities ranging from 143 mph to 450 mph (63.9 to 201.2 m/s) will penetrate wood samples ranging from soft to hard. This research suggests that the observed events can be explained rationally. The work also suggests that if straws penetrating into certain types of hardwoods
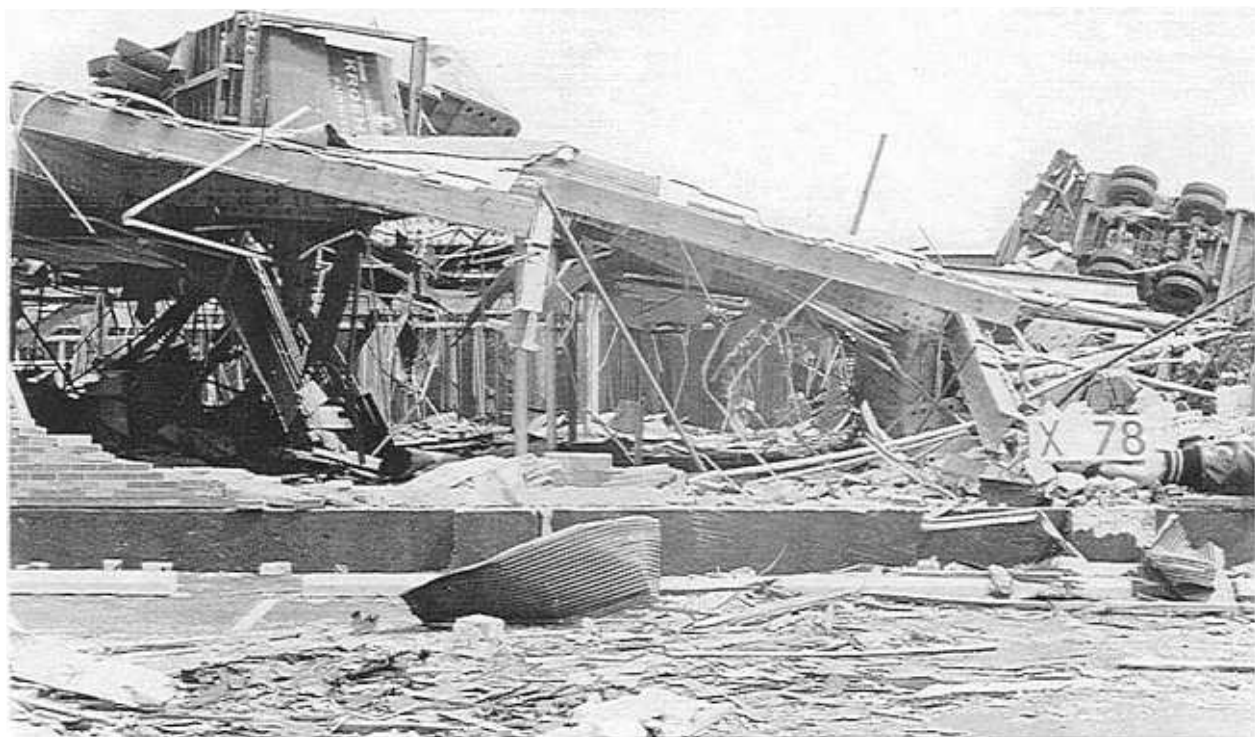
FIGURE 87. FURNITURE VANS ON BOWLING ALLEY ROOF FOLLOWING XENIA, OHIO TORNADO
OF APRIL 3, 1974. The empty vans had a large "flight parameter".

can be documented factually, knowledge of upper bound limits on tornadic windspeeds can be extended.

IX. UNUSUAL EVENTS

A. Commentary

Engineers who become committed to the design of buildings and facilities to resist the effects of the tornado continue to encounter popular concepts of tornadoes which assume that "mysterious forces" are at play (Minor, 1976). It is difficult for an engineer to be objective in the development and presentation of design criteria and tornado-resistant designs when he is faced with distorted perceptions of the tornado that have been engrained in our culture for many generations. This problem becomes particularly acute when the engineer must deal with the public directly--through school boards, in tornado shelter presentations, in windstorm related damage litigations, and in the promotion of wind-resistant design concepts in general.

A major objective of this report is to place the tornado into perspective from an engineering point of view. In this final section, several popular concepts of the tornado are addressed with the objective of establishing that the tornado's effects are both understood and bounded, and that events associated with tornadoes can be explained with current perceptions of the tornado's effects -- windspeeds, windfield geometry, and atmospheric pressure change. For completeness, several of the popular concepts addressed in detail elsewhere in this report are mentioned below.

B. Exploding Structures

Tornadoes do cause buildings to "explode". However, the cause of the walls and roof moving outward and upward seems to be wind related, rather than induced by atmospheric pressure change. Discussions of modes of building failure when an opening appears in a windward wall (Section III) and discussions of the character and magnitude of atmospheric pressure change (Section VII) support this observation.

C. Open Windows and Building Response

The question most often asked by the layman concerns the advisability of opening a window when a tornado strike is imminent. Discussions in Sections IV and VII indicate that an open window can help by relieving pressure on the roof (at the expense of the windward wall)

if the open window is in the leeward wall. Most often, however, the direction of an attacking wind will be unknown, even if the tornado approach direction is known; hence, opening a window has a good chance of being detrimental to the building. The act of opening a window, in itself, may be hazardous. Where "pressure relief" is concerned, most residences and commercial buildings have enough natural venting to relieve any change in atmospheric pressure which may occur. (One sq ft of opening per 1000 cu ft of volume, or 1/3 m^3 per 100 m^3 of volume, will "vent" the atmospheric pressure change effects of a severe tornado.) Finally, it is noted that severe winds act on a building before the largest portion of the atmospheric pressure change can become effective; hence, window failures or failures of other components are likely to "open" the structure to a greater degree than an open window would, if the tornado is severe enough to possess a dramatic pressure drop. As a result of these observations the authors advised the National Weather Service Disaster Preparedness Staff to delete reference to opening a window from tornado preparedness instructions to the public

D. Water Removal from Ponds

Reports of water being "sucked" from ponds and wells persist in the popular literature, although such occurrences cannot be substantiated either from analysis of tornado phenomenology or from analysis of field data. The tornado is a small vortex with low central pressure. However, the vortex is hardly small enough, nor the pressure low enough, to effect significant water removal through a "sucking" process. If a small vortex were centered over a body of water so that its maximum diameter were smaller than the pond (Fig. 88), then the effects of normal atmospheric pressure on the water surface outside of the tornado would tend to push water upward in the tornado core. (This is the same phenomenon which makes liquid rise in a soda straw.) While this geometry is possible, it can be seen that even an extreme pressure difference of 3 psi (200 mb) would cause water in the core to rise only about 6 ft (1.83 m). With tornado transit times over ponds or other bodies of water being relatively short, it is difficult to conjecture that very large volumes of water could be moved through this mechanism.

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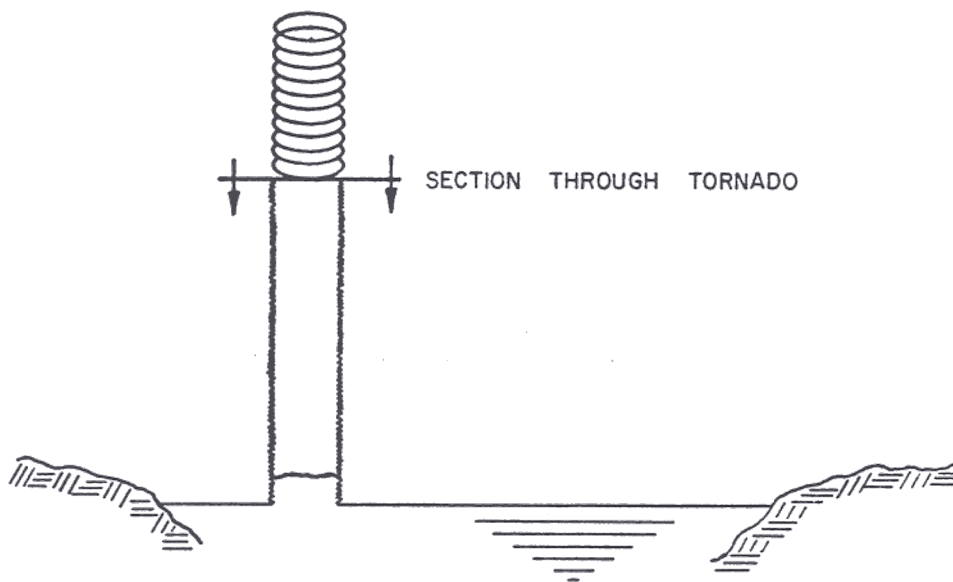
(a) SMALL TORNADO OVER A POND CAN RAISE WATER LEVEL ONLY A FEW FEET AT MOST

SECTION THROUGH TORNADO

SECTION THROUGH TORNADO
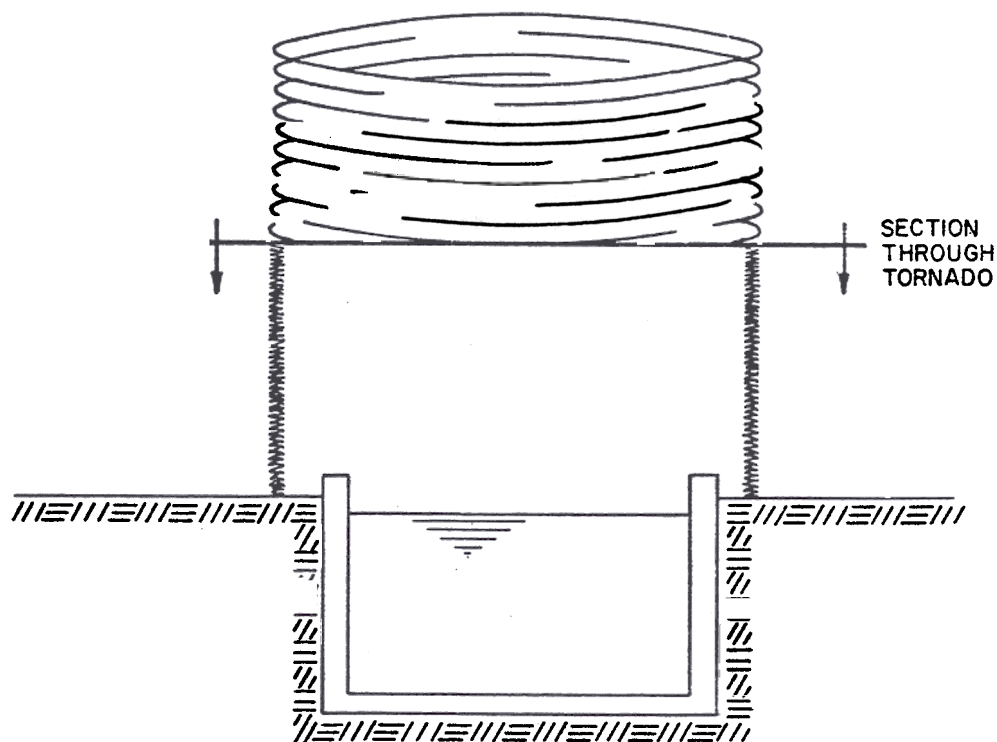
(b) LARGE TORNADO OVER A POOL CANNOT LIFT WATER

FIGURE 88. TORNADOES OVER POOLS OR PONDS CANNOT BE EXPECTED TO MOVE LARGE QUANTITIES OF WATER. The "sucking" mechanism is not a viable concept for water removal, although wind forces will cause dramatic spray phenomena.

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Photographs and eyewitness accounts reveal that water "sprays" upward to great heights when a tornado crosses onto water surfaces. It is expected that these events do occur as reported because the turbulent windfield surely generates waves and spray on the water surface which can be moved into the windfield. Water spray would act much as the dust in dust devils and in tornadoes which move over plowed fields. Waterspouts induce the spray phenomenon as well, usually on a smaller scale than the tornado.

Where opportunities for water removal have been presented, there seems to be no evidence of large volumes of water being moved. The Xenia Tornado of April 3, 1974 crossed a small lake as it approached Xenia High School. While the spray phenomenon was reported by some eyewitnesses, the water level in the lake was not altered (Fig. 89). A tornado passed directly over a swimming pool in Tulsa, Oklahoma on December 5, 1975 without removing any water (Fig. 90). A reported incident of a pool being "sucked dry" by the Omaha Tornado of May 6, 1975 proved to be a pool that was drained for cleaning (Fig. 91). Other pools in Drumright, Oklahoma and in Omaha, Nebraska also had opportunities to be affected by tornadoes which passed directly overhead but were not.

E.   Broom Straws and Planks

A very common concept is that tornaodes drive broom straws through wooden planks or posts. This topic is treated in detail in Section VIII (missiles). It is pointed out in scientific experimentation which reproduced the phenomenon in the laboratory that threshold speeds for driving broom straws into soft wood (pine and fir) are only 145-165 mph (64.8 - 73.8 m/s) (Keller and Vonnegut, 1976). As in the case cited above concerning water removal, neither scientific analysis nor field data substantiate the occurrence of phenomena which cannot be explained by currently held understandings of tornadoes. Investigators from Texas Tech University have looked for examples of straws being driven into planks in the wake of severe tornadoes and have found only a few -- mostly field straw impacting cedar fence posts, with the straw seemingly wedged between fibers on the bark.

FIGURE 89.

THE XENIA, OHIO TORNADO OF APRIL 3, 1974 CROSSED THE LAKE (UPPER RIGHT)
AS IT APPROACHED XENIA HIGH SCHOOL. The water level was not altered.
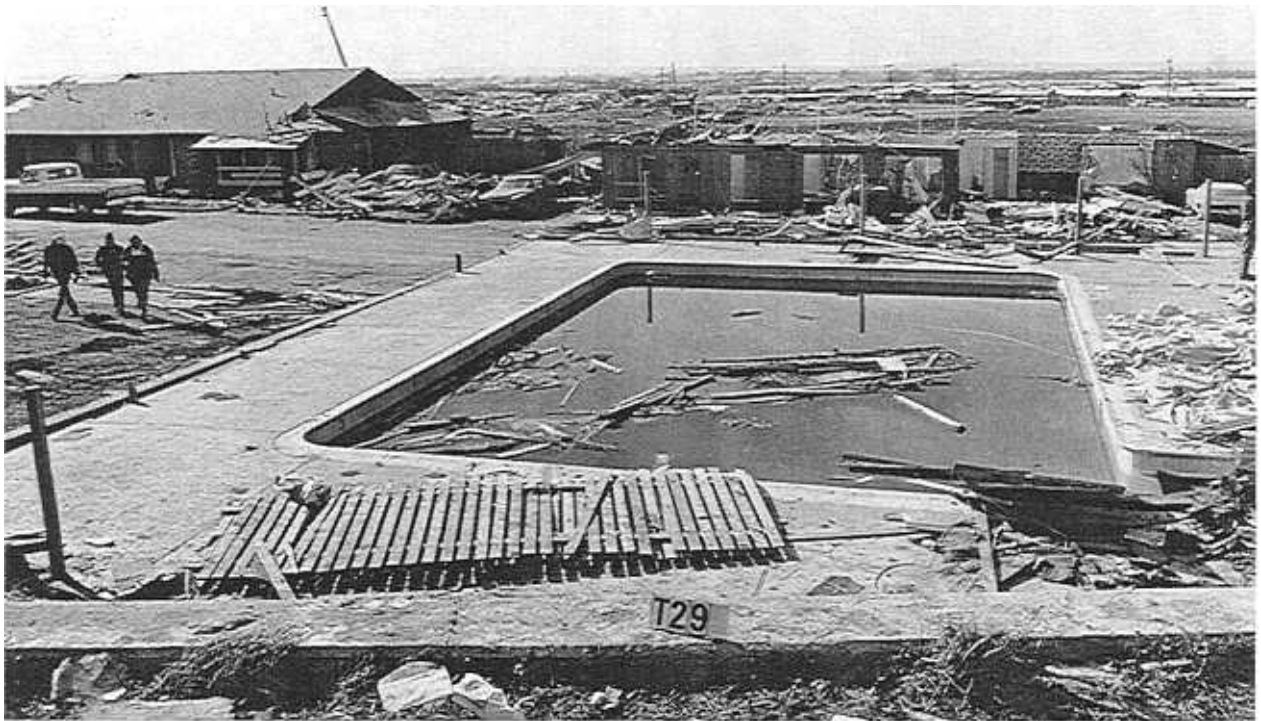
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FIGURE 90.   A TORNADO PASSED DIRECTLY OVER THIS SWIMMING POOL IN TULSA, OKLAHOMA
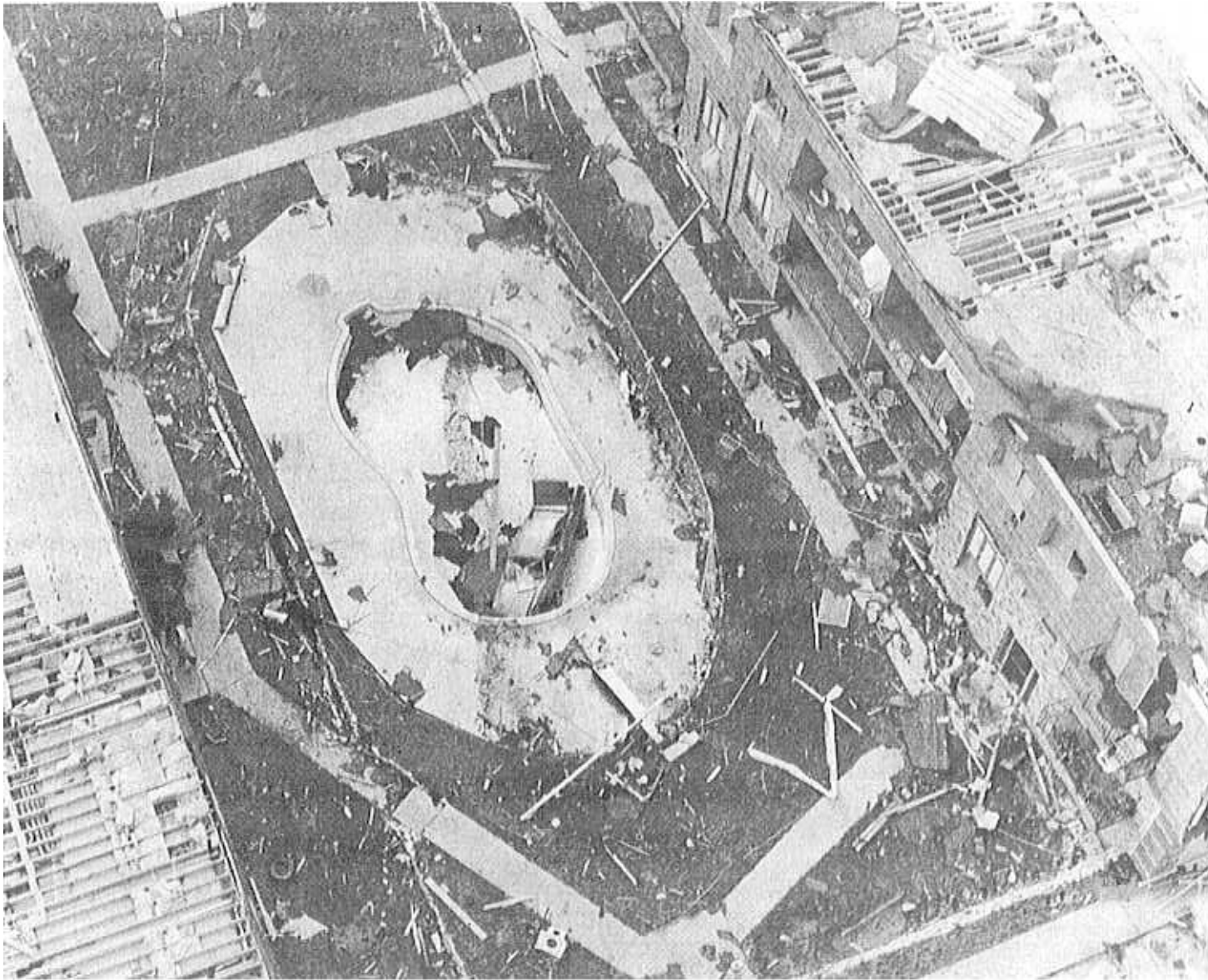ON DECEMBER 5, 1975.   No water was removed from the pool.

FIGURE 91. REPORT OF POOL IN OMAHA BEING "SUCKED" DRY PROVED TO BE A POOL EMPTY
FOR CLEANING. The car tumbled into the empty pool from an adjacent
parking lot.

F   Extreme Missiles

Stories persist about large and heavy objects being moved by tornadoes. It is pointed out (Section VIII) that large objects such as houses and mobile homes can be moved relatively easily by winds because of their relatively large "flight parameters" (C_D A/W). Hence, reports of houses being moved from foundations or overturned are not uncommon, especially if anchorages between houses and foundations are poor or non-existent. Perhaps the most dramatic missile events involve large timbers moved great distances. The 4 x 12 in. (152 x 381 mm) timber section which penetrated the residential wall in Plainview, Texas (Fig. 79) was carried 400 ft (122 m) or more while attached to a carport roof. This "airfoil" effect was also responsible for moving 6 x 15 in. (152 x 381 mm) timbers 1000 ft (305 m) in the May 6, 1975 Omaha Tornado (Fig. 92). The timbers were attached to a roof section lifted from Westgate Elementary School (Fig. 93). In this case eyewitnesses reported that the airfoil came apart on impact, sending the beams into the ground and damaging automobiles. When heavy objects are moved great distances, the most destructive effects of a tornado can be seen. However, even the dramatic image of 6 x 15 in. (152 x 381 mm) timbers flying through the air for thousands of feet can be explained by current perceptions of tornadic windspeeds (Section IV), of building failure modes (Section III), of missile injection mechanisms (Fig. 73), and of airfoil phenomena.

FIGURE 92.   LAMINATED WOOD TIMBERS 6 x 15 IN. (152 x 381 mm) AND 30 FT
(9.1 m) LONG WERE CARRIED MORE THAN 1000 FT (305 m) BY THE
OMAHA, NEBRASKA TORNADO OF MAY 6, 1975. The timbers (top)
impacted upon the automobile (below).

FIGURE 93. THE SOURCE OF THE TIMBER MISSILES (FIG. 92) WAS THE
WESTGATE ELEMENTARY SCHOOL. Laminated wood beams
formed integral parts of a roofing system, parts of
which became airborne.

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X. CONCLUSION

Throughout the report the contributions of the investigators have
been presented in terms of their scientific or engineering orientation.
Further, certain of the engineering-oriented understandings of the tor-
nado phenomenon have been placed into use, while others are advanced
with the prospect that use will be made of them in the future. In
this concluding section, understandings of the tornado phenomenon con-
tributed by the authors herein are summarized according to their type
(scientific or engineering) and, in the case of engineering contri-
butions, their use (currently used in practice or available for use
in the near future).

A.   Scientific Understandings

Detailed examination and analysis of damage and debris from more
than 30 windstorm investigations have led the authors to conclusions
regarding maximum windspeeds, near-ground windfield geometry, the per-
formance of buildings as indicators of windspeed and windfield geometry,
and atmospheric pressure change at ground level.

1.   Windspeeds in Tornadoes

The basic conclusion advanced is that no conclusive evidence
can be found that ground level windspeeds in tornadoes exceed 250 mph
(112 m/sec). This observation by the authors and the work of meteorolo-
gists who work with vortex models and photogrammetric analyses lead the
authors to conclude that maximum tornadic windspeeds at ground level
do not exceed the range 250-275 mph (112-123 m/sec). This conclusion
is reported in the Proceedings of the Symposium on Tornadoes (Peterson,
1976) and is generally consistent with similar judgments advanced by
others.

2.   Windfield Geometry

The tendency of many single buildings to fail because of
structural weaknesses or an inopportune orientation with respect to the
approaching wind produces many "streaks" of debris in the damage pat-
tern. This observation does not preclude the possibility that there
are extreme local perturbations (e.g. suction vortices) in the wind-
field. However, it must be concluded that the observation of a "streak"

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of debris does not establish the passage of an extreme wind perturbation (e.g. a suction vortex) over the building in question. Further, there does not seem to be any order in the damage pattern which would suggest near-ground windfield geometry that is more orderly than the circulation associated with the parent vortex. The exact character of the near-ground windfield is a question which remains open to further research.

3. Performance of Buildings

The authors have concluded that the performance of buildings in windstorms is related directly to the degree of engineering attention given to the design and construction of a building. Hence, the presence of an undamaged engineered building in the path of a tornado should not be viewed as evidence that the tornado "skipped over" the building; rather, this situation should reflect the observation that well-engineered buildings can be expected to perform well in the face of a tornado. Finally, while houses (non-engineered structures) are vulnerable to wind-inspired damage and are difficult to analyze for damaging windspeeds, certain types of housing (generally code-enforced housing construction) can be used as windspeed indicators for windspeed occurrences which do not exceed 150 mph.

4. Atmospheric Pressure Change

Observations by the authors and calculations of air exchange rates in typical buildings have led to the conclusion that atmospheric pressure change plays, at most, a minor role in the building damage mechanism. Further, no evidence can be found in tornado damaged areas which suggests that ground level values of atmospheric pressure change are as large as values obtained from the cyclostrophic equation at higher elevations in the vortex.

B. Engineering Understandings

Some of the new understandings of tornado related phenomena have been placed into professional practice, while others have not. Summarized below are the observations of the authors regarding the incorporation of tornado technology into practice.

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1.   Concepts Currently in Practice   -

   °The maximum windspeed values reported above have produced
shelter designs for residences, schools, and public buildings which
can be expected to perform well in the face of any tornado event.

   °Tornado-structure interaction phenomena as currently under-
stood by the engineer are being used in the nuclear industry and in
the design of certain other critical facilities.

   °Data from tornado missile incidents have become integral
parts of design criteria for shelters, nuclear related structures,
and critical facilities.

2.   Concepts With Potential for Use

   °The characterization of tornado occurrences as windspeed-
oriented risk models is an established procedure. These risk models
could be used to specify wind loads for a wide range of conventional
buildings and would produce economic designs commensurate with ac-
ceptable levels of risk.

   °Rational analysis of the tornado and its effects lead the
engineer to conclude that there are no physical phenomena at work be-
yond those commonly acknowledged--violently rotating winds with atten-
dant changes in pressure. Hence, current perceptions of tornadic
windspeeds and atmospheric pressure change can be employed effectively
in the design of structures by engineers.

   °Examination of damage documentations leads to the conclusions
that most building damage is caused by windspeeds in the 75-125 mph
range and that most of this damage is the result of anchorage or connec-
tion failures. These conclusions mean that relatively small invest-
ments in improving these details can produce significant reductions in
the cost of damage caused by windstorms.

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